

MesonNet Workshop on Meson Transition Form Factors

May 29–30, 2012 in Cracow, Poland

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ABSTRACT

The mini-proceedings of the Workshop on Meson Transition Form Factors held in Cracow from May 29th to 30th, 2012 introduce the meson transition form factor project with special emphasis on the interrelations between the various form factors (on-shell, single off-shell, double off-shell). Short summaries of the talks presented at the workshop follow.

The web page of the conference, which contains all talks, can be found at

http://www2.fz-juelich.de/ikp//mesonnet/meetings/2012_ff_workshop.shtml

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Contents

1	Introduction – Scope of the workshop	4
	<i>S. Eidelman et al.</i>	
1.1	Motivation	4
1.2	Generalities on transition form factors	5
1.3	Dalitz decays	12
1.4	Radiative and hadronic anomalous processes	13
1.5	A naive Vector Meson Dominance model picture	13
1.A	List of processes	15
2	Short summaries of the talks	21
2.1	Muon $g - 2$ from τ and e^+e^- data	21
	<i>F. Jegerlehner</i>	
2.2	A lattice study of the leading order hadronic contribution to the muon anomalous magnetic moment	23
	<i>K. Jansen</i>	
2.3	Confronting the scan, ISR and tau dipion spectra within a global model . . .	24
	<i>M. Benayoun</i>	
2.4	Light Meson Decays with WASA-at-COSY	25
	<i>H. Bhatt</i>	
2.5	Recent results and perspectives on pseudoscalar mesons and form factors at BES III	27
	<i>E. Prencipe</i>	
2.6	Measurements of the photon-meson transition form factors	29
	<i>V.P. Druzhinin</i>	
2.7	Measurement of $\gamma\gamma^* \rightarrow \pi^0$ transition form factor at Belle	30
	<i>S. Uehara</i>	
2.8	Form factors and hadronic contributions to $(g - 2)_\mu$ from Dyson-Schwinger equations	32
	<i>C. S. Fischer</i>	
2.9	Hadronic contribution to $(g - 2)_\mu$ from e^+e^- annihilations and τ decays . . .	33
	<i>B. Malaescu</i>	
2.10	Hadronic light-by-light scattering in the muon $g - 2$: impact of transition form factor measurements	34
	<i>A. Nyffeler</i>	
2.11	Charged pion contribution to light-by-light and the muon $g - 2$	35
	<i>K. Engel</i>	
2.12	Pseudoscalar Transition Form Factors @ KLOE-2 and BGO-OD	36
	<i>M. Mascolo</i>	

2.13	Meson Decay Program with Crystal Ball at MAMI	37
	<i>M. Unverzagt</i>	
2.14	Transition Form Factors from CMD-2/CMD-3	38
	<i>S. Eidelman</i>	
2.15	Study of the Process $e^+e^- \rightarrow \omega\pi^0 \rightarrow \pi^0\pi^0\gamma$ in c.m. Energy Range 1.05– 2.0 GeV at SND	40
	<i>L. Kardapoltsev</i>	
2.16	Transition Form Factors with HADES	42
	<i>W. Przygoda</i>	
2.17	Some comments on CLEO results and their interpretation	45
	<i>V. Savinov</i>	
2.18	A new parameterization for the pion vector form factor	47
	<i>C. Hanhart</i>	
2.19	High accuracy pion phase shifts and light scalar mesons	48
	<i>J. R. Peláez</i>	
2.20	Roy–Steiner equations for $\gamma\gamma \rightarrow \pi\pi$	49
	<i>M. Hoferichter</i>	
2.21	A Dispersive Treatment of $K_{\ell 4}$ Decays	51
	<i>P. Stoffer</i>	
2.22	$\eta, \eta' \rightarrow \pi^+\pi^-\gamma$ – A model-independent approach	52
	<i>A. Wirzba</i>	
2.23	The $\omega/\phi \rightarrow \pi^0\gamma^*$ transition form factors in dispersion theory	53
	<i>S. P. Schneider</i>	
2.24	A Rational Approach to Meson Transition Form Factors	54
	<i>P. Masjuan</i>	
2.25	Radiative transitions of vector mesons	55
	<i>S. Ivashyn</i>	
2.26	Decays with Vector Mesons	59
	<i>C. Terschlüsen</i>	
2.27	Meson form factors in amplitudes for three-body B decays	60
	<i>L. Leśniak</i>	
2.28	ChPT calculations of form factors	61
	<i>K. Kampf</i>	
2.29	Pion-photon transition form factor at the crossroads	62
	<i>N. G. Stefanis</i>	
2.30	Light pseudoscalar meson decays into lepton pair	64
	<i>A. E. Dorokhov</i>	
2.31	The hadronic light-by-light contribution to the muon anomalous magnetic moment	66
	<i>J. Bijnens</i>	

3 List of participants

67

1 Introduction – Scope of the workshop

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1.1 Motivation

Transition form factors are an important ingredient in the detailed understanding of the nature of mesons and their underlying quark and gluon structure. Lately, meson transition form factors have been widely discussed for a number of reasons:

- The field is relevant to better quantify the Standard Model value for the anomalous magnetic moment of the muon $(g - 2) (a_\mu)$. In particular for the calculation of the hadronic light-by-light (LbL) contribution [1–4], see Fig. 1, one needs to know various form factors describing the interaction of photons with hadrons.
- Precise knowledge of the lepton pair mass spectra is mandatory in a search for the quark-gluon plasma and medium modifications of hadron properties in heavy-ion collisions [5].
- It is a field of hadronic physics where high-precision measurements are possible and theoretical calculations are therefore highly needed [6].

A detailed analysis of various theoretical approaches to LbL in Ref. [3] leads to $a_\mu^{\text{LbL, had}} = (10.5 \pm 2.6) \cdot 10^{-10}$. The estimation of Ref. [4] leads to an even larger uncertainty, $(11.6 \pm 3.9) \cdot 10^{-10}$. This uncertainty will very soon limit the precision of the whole hadronic contribution to a_μ . Note that there has been significant progress recently in computing the leading-order hadronic contribution to a_μ on the lattice [7], providing a prospect that lattice calculations can contribute to resolve the $a_m u$ discrepancy in the future.

The leading contribution to the blob denoted by “had” in Fig. 1 is given by the exchange of light hadrons that couple to two photons—since the anomalous magnetic moment is a

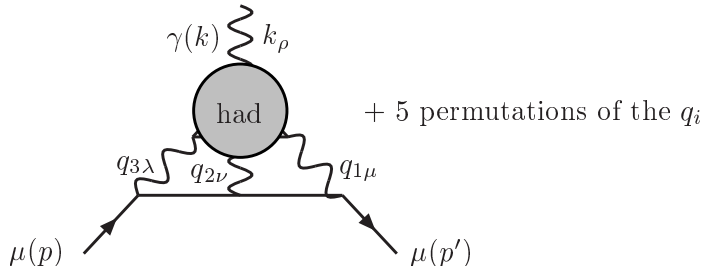


Figure 1: Light-by-light scattering contribution. Figure taken from Ref. [4].

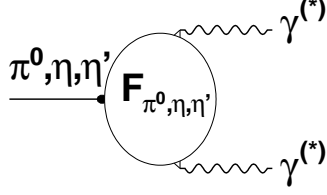


Figure 2: General $P\gamma^*\gamma^*$ vertex described by a transition form factor.

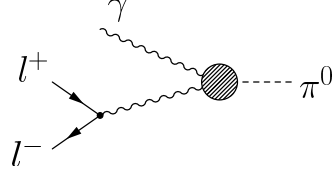


Figure 3: Pion transition form factor.

static quantity, one expects the LbL contribution from these diagrams to scale as $1/m_{\text{had}}^2$, with m_{had} for the mass of the exchange hadron, leading to a significant suppression of heavier intermediate states.

Therefore, the contribution of the lightest state, the pion, is very important. What enters in the pion-exchange contribution to LbL in the $(g-2)$ is a form factor that describes the interaction of off-shell pions with off-shell (or on-shell) photons $\pi^{0*} \rightarrow \gamma^{(*)}\gamma^{(*)}$, as defined in Refs. [8–11]. While such an off-shell pion form factor is not a physical quantity and therefore model-dependent, any successful model needs to correctly describe the pion transition form factor, $\pi^0 \rightarrow \gamma^{(*)}\gamma^{(*)}$, where the pion is on-shell, but the photons can be real (γ) or virtual (γ^*), with the virtuality being spacelike (electron scattering) or timelike (dilepton production or e^+e^- annihilation). Information on the transition form factor can therefore help to constrain the models used to evaluate hadronic LbL scattering.

1.2 Generalities on transition form factors

A transition form factor $\mathcal{F}_P(q_1^2, q_2^2)$ is a scalar function of the four-momentum transfer squared of the virtual photons ($q_{1,2}^2$) describing the vertex in Fig. 2 and defined as

$$\mathcal{A}(P \rightarrow \gamma^*\gamma^{(*)}) = q_1^\mu \epsilon_1^\nu q_2^\alpha \epsilon_2^\beta \epsilon_{\mu\nu\alpha\beta} \mathcal{F}_P(q_1^2, q_2^2) \quad (1)$$

and

$$\frac{m_P^3}{64\pi} |\mathcal{F}_P(q_1^2 = 0, q_2^2 = 0)|^2 = \Gamma(P \rightarrow \gamma\gamma). \quad (2)$$

One often uses a normalized transition form factor:

$$F_P(q_1^2, q_2^2) = \frac{\mathcal{F}_P(q_1^2, q_2^2)}{\mathcal{F}_P(q_1^2 = 0, q_2^2 = 0)}. \quad (3)$$

For example, for the neutral pion physical processes include the following.

- $\pi^0 \rightarrow 2\gamma$: this is well described by the chiral anomaly encoded in the Wess–Zumino–Witten action, see, e.g., Refs. [12, 13].
- $\pi^0 \rightarrow \gamma e^+e^-$ and $\pi^0 \rightarrow e^+e^- e^+e^-$: as an illustration, see Fig. 3.
- $e^+e^- \rightarrow \pi^0 e^+e^-$: here two virtual photons can fuse “in flight” to form the pion.¹

¹In principle, this process interferes at the amplitude level with e^+e^- annihilation and successive emission of a pion and virtual photon; dominance of the virtual-photon-fusion process can be ensured by appropriate kinematical cuts.

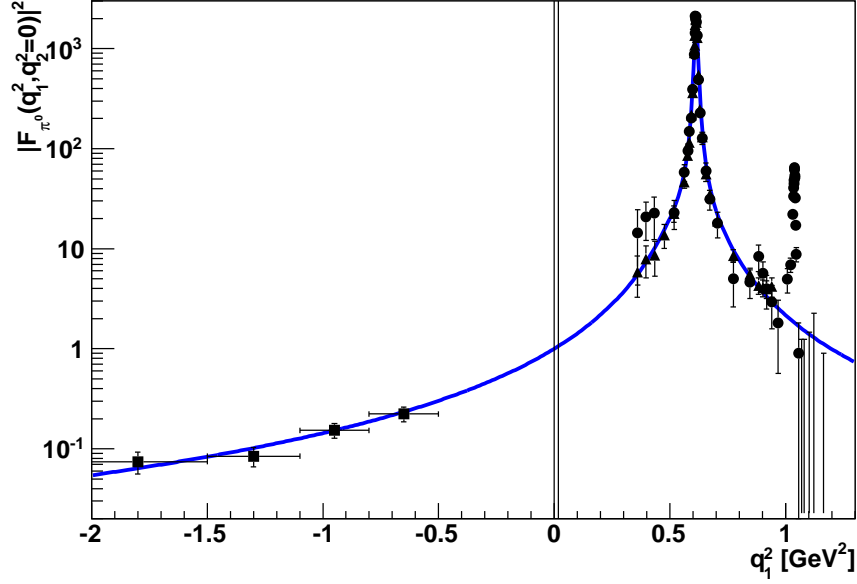


Figure 4: Single off-shell π^0 meson transition form factor in the low $|q^2|$ region from SND [15] and CMD-2 [16] data on the reaction $e^+e^- \rightarrow \pi^0\gamma$ and CELLO data on the reaction $e^+e^- \rightarrow e^+e^-\gamma^*\gamma^* \rightarrow e^+e^-\pi^0$ [17].

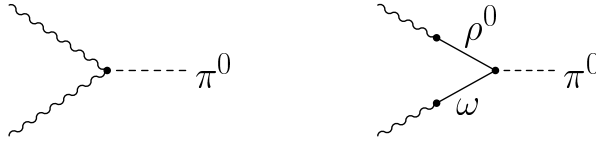


Figure 5: Contributions to the pion transition form factor. Wavy lines denote real or virtual photons.

- Another process involving the pion transition form factor is a very rare direct dilepton decay $\pi^0 \rightarrow e^+e^-$. Two photons emitted in this process convert to a dilepton by lepton exchange, see Fig. 34c in Ref. [6]. The pion transition form factor enters the corresponding “QED loop”; see, e.g., Ref. [14].

Available data on $|F_{\pi^0}(q^2, 0)|$ for low $|q^2|$ values are presented in Fig. 4. For theoretical calculations of the pion form factor see, e.g., Refs. [18–21] and references therein. The models either use strict vector meson dominance [22] (right diagram in Fig. 5), or, as, e.g., in Ref. [20], include point interactions in addition (the left diagram in Fig. 5). For a review on vector mesons and their interactions, see also Ref. [23]. In Ref. [1] the two-photon data on the production of pseudoscalar mesons (π^0 , η , η') [24] was used to model the transition form factors needed in the evaluation of $a_\mu^{\text{LbL, had}}$.

In Table 1 we list the information on the branching fractions of π^0 decays together with the corresponding theoretical predictions. The branching ratios largely follow the naive scaling as $1 : \alpha_{\text{QED}} : \alpha_{\text{QED}}^2 : \alpha_{\text{QED}}^2/(4\pi)^2$, where the factor $(4\pi)^2$ is present since in the Standard Model the leading contribution to $\pi^0 \rightarrow e^+e^-$ appears at one loop. Note that between the most accurate calculation for $\pi^0 \rightarrow e^+e^-$ and the corresponding experimental value there is a more than 3σ discrepancy. For asymptotically large virtualities there are QCD constraints on the pion transition form factor, see, e.g., Refs. [14, 31, 32]. These might

Mode	\mathcal{B}^{exp}	Ref.	\mathcal{B}^{th}	Ref.
$\pi^0 \rightarrow \gamma\gamma$	$(98.823 \pm 0.034)\%$	[25]	–	–
$\pi^0 \rightarrow e^+e^-\gamma$	$(1.174 \pm 0.035)\%$	[25]	$(1.182 \pm 0.003)\%$	[26]
$\pi^0 \rightarrow e^+e^-e^+e^-$	$(3.34 \pm 0.16) \cdot 10^{-5}$	[25]	$3.39 \cdot 10^{-5}$	[21]
$\pi^0 \rightarrow e^+e^-$	$(7.48 \pm 0.29 \pm 0.25) \cdot 10^{-8}$	[27] ²	$(6.33 \pm 0.19) \cdot 10^{-8}$	[28]
			$(6.1 \pm 0.3) \cdot 10^{-8}$	[29]
			$(6.2 \pm 0.1) \cdot 10^{-8}$	[30]

Table 1: Branching fractions of π^0 radiative and leptonic decays. See Ref. [21] for further theoretical references.

Mode	\mathcal{B}^{exp}	Ref.	\mathcal{B}^{th}	Ref.
$\eta \rightarrow \gamma\gamma$	$(39.31 \pm 0.20)\%$	[25]	–	–
$\eta \rightarrow e^+e^-$	$< 5.6 \cdot 10^{-6}$	[40]	$(4.5 \pm 0.2) \cdot 10^{-9}$	[29]
			$5.24 \cdot 10^{-9}$	[30]
$\eta \rightarrow \mu^+\mu^-$	$(5.8 \pm 0.8) \cdot 10^{-6}$	[25]	$(5.5 \pm 0.8) \cdot 10^{-6}$	[29]
			$4.64 \cdot 10^{-6}$	[30]
$\eta \rightarrow e^+e^-\gamma$	$(6.9 \pm 0.4) \cdot 10^{-3}$	[25]	$6.5 \cdot 10^{-3}$	[21]
$\eta \rightarrow \mu^+\mu^-\gamma$	$(3.1 \pm 0.4) \cdot 10^{-4}$	[41]	$3.0 \cdot 10^{-3}$	[21]
$\eta \rightarrow e^+e^-e^+e^-$	$(2.4 \pm 0.2 \pm 0.1) \cdot 10^{-5}$	[42]	$2.67 \cdot 10^{-5}$	[21]
$\eta \rightarrow e^+e^-\mu^+\mu^-$	$< 1.6 \cdot 10^{-4}$	[43]	$(2.2 \pm 0.1) \cdot 10^{-6}$	[21]
$\eta \rightarrow \mu^+\mu^-\mu^+\mu^-$	$< 3.6 \cdot 10^{-4}$	[43] ³	$(3.8 \pm 0.1) \cdot 10^{-9}$	[21]

Table 2: Branching fractions of η radiative and leptonic decays. Ref. [21] serves as an example for predictions of VMD-inspired models; see references therein for further literature.

be at odds with recent experimental results from BaBar [33]; see, however, also the recent Belle results [34].

Due to the approximate SU(3) flavor symmetry, the pion transition form factor is closely related to the corresponding transition form factor of the η meson and, via η - η' mixing, also to the transition form factor of the η' . In fact, the whole discussion of η - η' mixing, interesting in its own right, is strongly based on these transition form factors [35–37].

Both processes $\pi^0 \rightarrow \gamma\gamma^*$ and $\eta \rightarrow \gamma\gamma^*$ can be described by vector meson dominance [6]. For the η this is illustrated with the available low- q^2 data on $|F_\eta(q^2, 0)|$ in Fig. 6. Note that this does not necessarily mean that the double-virtual processes $\pi^0/\eta \rightarrow \gamma^*\gamma^*$ would be also well described by vector meson dominance. Indeed, some theories show deviations [20, 39]. In Tables 2 and 3 we show the branching fractions of the η and η' non-hadronic decays.

²The value given in Ref. [25], $(6.46 \pm 0.33) \cdot 10^{-8}$, is not corrected for final state radiation.

³Since the authors do not distinguish between the $\mu^+\mu^-\mu^+\mu^-$ and $\mu^+\mu^-\pi^+\pi^-$ final states, the upper limit is for a sum of the branching fractions for the two modes.

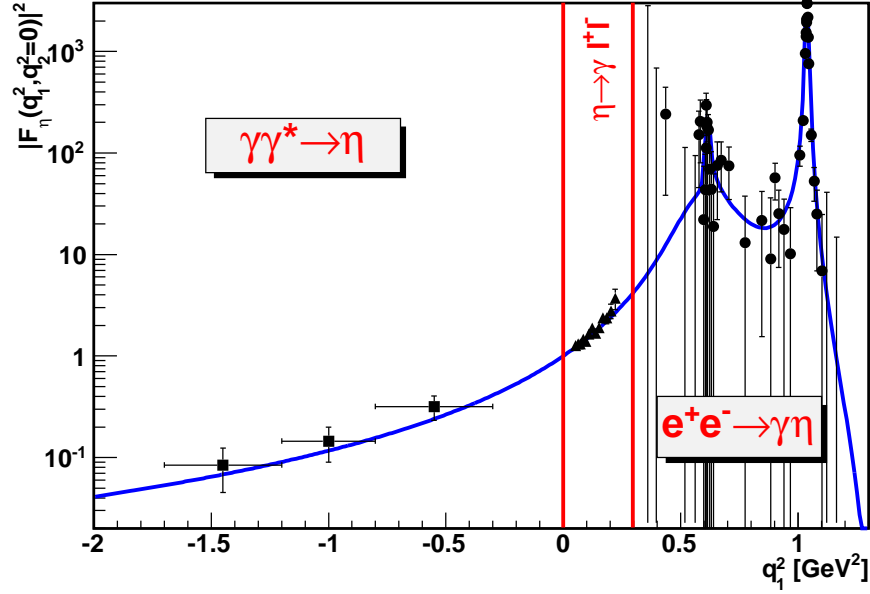


Figure 6: Single off-shell η meson transition form factor from NA60 data on $\eta \rightarrow \gamma \mu^+ \mu^-$ decay [38]; from SND [15] and CMD-2 [16] data on the reaction $e^+ e^- \rightarrow \eta \gamma$ reaction, and CELLO data on the reaction $e^+ e^- \rightarrow e^+ e^- \gamma^* \gamma^* \rightarrow e^+ e^- \eta$ [17].

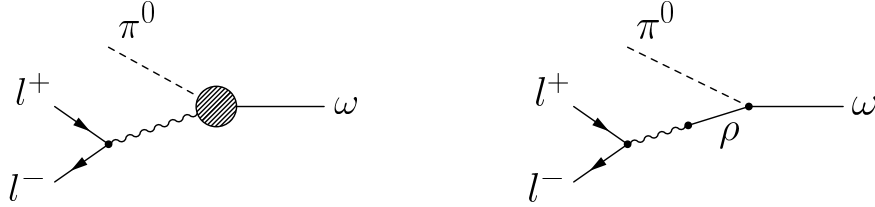


Figure 7: Left: transition form factor of omega to pion. Right: tree-level contribution to the omega transition form factor.

Since vector mesons are relevant as intermediate states for the transition form factors of pseudoscalar mesons, there is another source of information, namely the transition form factors of vector mesons to pseudoscalar mesons. These involve processes like

- $\omega \rightarrow \pi^0 l^+ l^-$ where $l = e, \mu$; see Fig. 7 for illustration. This process shows a dramatic deviation from the vector meson dominance picture [38, 47], see the data in Fig. 8.
- $e^+ e^- \rightarrow \pi^0 \omega$: previously studied in Novosibirsk with SND [48] and CMD-2 [49].
- ϕ instead of ω in the previous processes and/or η instead of π^0 (in part measured): it would be important to clarify whether also in these processes the drastic deviation from vector meson dominance seen in $\omega \rightarrow \pi^0 \mu^+ \mu^-$ shows up. Of particular importance is $\phi \rightarrow \pi^0 l^+ l^-$, where the peak mass of the ρ meson is in the kinematically allowed region [51].
- $\eta' \rightarrow \omega \gamma$ (measured) and $\eta' \rightarrow \omega e^+ e^-$ (not measured).

Mode	\mathcal{B}^{exp}	Ref.	\mathcal{B}^{th}	Ref.
$\eta' \rightarrow \gamma\gamma$	$(2.18 \pm 0.08)\%$	[25]	—	—
$\eta' \rightarrow e^+e^-$	$< 2.1 \cdot 10^{-7}$	[44]	$1.86 \cdot 10^{-10}$	[30]
$\eta' \rightarrow \mu^+\mu^-$	—	—	$1.30 \cdot 10^{-7}$	[30]
$\eta' \rightarrow e^+e^-\gamma$	$< 9 \cdot 10^{-4}$	[45]	$(4.4 \pm 0.2) \cdot 10^{-4}$	[21]
$\eta' \rightarrow \mu^+\mu^-\gamma$	$(1.07 \pm 0.26) \cdot 10^{-4}$	[46]	$(0.90 \pm 0.06) \cdot 10^{-4}$	[21]
$\eta' \rightarrow e^+e^-e^+e^-$	—	—	$(2.1 \pm 0.1) \cdot 10^{-6}$	[21]
$\eta' \rightarrow e^+e^-\mu^+\mu^-$	—	—	$(7.6 \pm 0.6) \cdot 10^{-7}$	[21]
$\eta' \rightarrow \mu^+\mu^-\mu^+\mu^-$	—	—	$(2.1 \pm 0.2) \cdot 10^{-8}$	[21]

Table 3: Branching fractions of η' radiative and leptonic decays. See Ref. [21] for further theoretical references.

Mode	\mathcal{B}^{exp}	Ref.	\mathcal{B}^{th}	Ref.
$\omega \rightarrow \pi^0 e^+e^-$	$(7.7 \pm 0.6) \cdot 10^{-4}$	[25]	$(8.1 \pm 0.1) \cdot 10^{-4}$	[54]
			$(7.6 \dots 8.1) \cdot 10^{-4}$	[51]
$\omega \rightarrow \pi^0 \mu^+\mu^-$	$(1.73 \pm 0.25 \pm 0.14) \cdot 10^{-4}$	[38]	$(1.16 \pm 0.07) \cdot 10^{-4}$	[54]
	$(0.96 \pm 0.23) \cdot 10^{-4}$	[56]	$(0.94 \dots 1.00) \cdot 10^{-4}$	[51]
$\omega \rightarrow \eta e^+e^-$	$< 1.1 \cdot 10^{-5}$	[57]	$(3.20 \pm 0.10) \cdot 10^{-9}$	[54]
$\omega \rightarrow \eta \mu^+\mu^-$	—	—	$(1.00 \pm 0.00) \cdot 10^{-9}$	[54]

Table 4: Branching fractions of ω conversion decays.

The measured branching ratios for these vector-meson-conversion decays are collected in Tables 4 and 5, compared to theoretical predictions. Some of these vector-to-pseudoscalar transition form factors have been calculated in Refs. [19, 51–55]. The relevant diagram in the vector-meson-dominance picture is depicted in Fig. 7 (right). Note the intimate relation of this diagram with Fig. 5 (right).

To clarify the relation between the vector-meson-conversion and the pseudoscalar transition form factors a little further, let us consider in particular the pion transition form factor. It can be characterized in the following way: because of isospin and G-parity, one of the virtual photons couples to an isovector (v) and the other to an isoscalar (s) state. Therefore, the pion transition form factor can be written as

$$F_{\pi^0}(q_1^2, q_2^2) = F_{vs}(q_1^2, q_2^2) + F_{sv}(q_1^2, q_2^2). \quad (4)$$

In $F_{ij}(q_1^2, q_2^2)$ the first/second index refers to the photon with momentum q_1/q_2 . If $\sqrt{q_2^2}$ is close to a resonance mass, M_ω or M_ϕ , one can approximately neglect $F_{sv}(q_1^2, q_2^2)$ —provided $\sqrt{q_1^2}$ is not also close to a resonance mass. Using the Breit–Wigner formula [25], the quantity

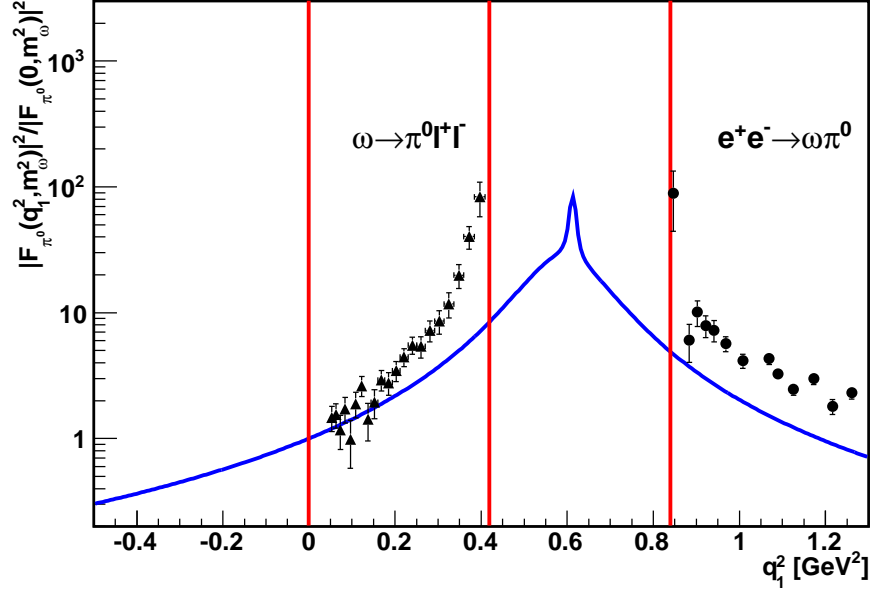


Figure 8: Data on the ω transition form factor $|F_{\pi^0}(q_1^2, M_\omega^2)|^2/|F_{\pi^0}(0, M_\omega^2)|^2$ from NA60 data on $\omega \rightarrow \pi^0 \mu^+ \mu^-$ decay [38] and from SND [48], CMD-2 [49], and KLOE [50] experiments on the $e^+ e^- \rightarrow \omega \pi^0$ reaction.

Mode	\mathcal{B}^{exp}	Ref.	\mathcal{B}^{th}	Ref.
$\phi \rightarrow \pi^0 e^+ e^-$	$(1.12 \pm 0.28) \cdot 10^{-5}$	[25]	$(1.39 \dots 1.53) \cdot 10^{-5}$	[51]
$\phi \rightarrow \pi^0 \mu^+ \mu^-$	—	—	$(3.7 \dots 4.1) \cdot 10^{-6}$	[51]
$\phi \rightarrow \eta e^+ e^-$	$(1.15 \pm 0.10) \cdot 10^{-4}$	[25]	$(1.09 \pm 0.06) \cdot 10^{-4}$	[54]
$\phi \rightarrow \eta \mu^+ \mu^-$	$< 9.4 \cdot 10^{-6}$	[58]	$(6.44 \pm 0.69) \cdot 10^{-6}$	[54]

Table 5: Branching fractions of ϕ conversion decays.

$F_{vs}(q_1^2, q_2^2)$ and therefore F_{π^0} can be approximated by

$$F_{\pi^0}(q_1^2, q_2^2) \approx f_{V \rightarrow \pi}(q_1^2) \frac{1}{q_2^2 - M_V^2 + i M_V \Gamma_{\text{tot}}} g_{V\gamma} \quad \text{for } q_2^2 \approx M_V^2, \quad (5)$$

where $f_{V \rightarrow \pi}(q_1^2)$ is an appropriately normalized form factor of the transition $V \rightarrow \pi^0 \gamma^*$ and Γ_{tot} the total width of the isoscalar vector meson V . This yields

$$\frac{F_{\pi^0}(q_1^2, M_V^2)}{F_{\pi^0}(0, M_V^2)} \approx \frac{f_{V \rightarrow \pi}(q_1^2)}{f_{V \rightarrow \pi}(0)} = F_{V \rightarrow \pi}(q_1^2), \quad (6)$$

where the vector-to-pion transition form factor $F_{V \rightarrow \pi}$ is normalized to 1 at the photon point.

A transition of the omega meson to the pion is given by the two-dimensional π^0 form factor as: $|F_{\pi^0}(q_1^2, M_\omega^2)|^2/|F_{\pi^0}(0, M_\omega^2)|^2$. It was measured in $\omega \rightarrow \pi^0 \ell^+ \ell^-$ as well as in the reaction $e^+ e^- \rightarrow \omega \pi^0$. The results are shown in Fig. 8 together with naive VMD predictions. Note that the region around $q_1^2 \approx M_\omega^2$ is just included for completeness. There, Eqs. (5) and (6) do not provide a good approximation.

$b_{\pi^0}(q^2)$ [GeV ⁻²]		
$b_{\pi^0}(q^2 = 0)$	1.79 ± 0.14	CELLO [17]
$b_{\pi^0}(q^2 = 0.613\text{GeV}^2)$	2.4 ± 0.2	Lepton-G [56]
$b_{\pi^0}(q^2 = 0.613\text{GeV}^2)$	$2.24 \pm 0.06 \pm 0.02$	NA60 [38]
$b_{\pi^0}(q^2 = 0.613\text{GeV}^2)$	$2.241 \pm 0.025 \pm 0.028$	NA60 [47]
$b_\eta(q^2)$ [GeV ⁻²]		
$b_\eta(q^2 = 0)$	1.9 ± 0.4	Lepton-G [41]
$b_\eta(q^2 = 0)$	1.42 ± 0.21	CELLO [17]
$b_\eta(q^2 = 0)$	$1.95 \pm 0.17 \pm 0.05$	NA60 [38]
$b_\eta(q^2 = 0)$	$1.950 \pm 0.059 \pm 0.042$	NA60 [47]
$b_\eta(q^2 = 0)$	$1.92 \pm 0.35 \pm 0.13$	CB/TAPS [59]
$b_\eta(q^2 = 1.040\text{GeV}^2)$	3.8 ± 1.8	SND [15]
$b_\eta(q^2 = 1.040\text{GeV}^2)$	2.63 ± 0.15	KLOE (prel.) [60]

Table 6: Summary of the available experimental data on $b_\eta(q^2)$ and $b_{\pi^0}(q^2)$.

A quantity often considered in the context of transition form factors is the form factor slope

$$b_P = \left. \frac{\partial \ln F(q^2, 0)}{\partial q^2} \right|_{q^2=0}, \quad (7)$$

which can be generalized to

$$b_P(q_2^2) = \left. \frac{\partial \ln |F(q_1^2, q_2^2)|}{\partial q_1^2} \right|_{q_1^2=0}. \quad (8)$$

Experimental data on the slope parameters for the π^0 transition form factor (both for $q^2 = 0$ and $q^2 = M_\omega^2$) and the η transition form factor (for $q^2 = 0$ and $q^2 = M_\phi^2$) are shown in Table 6, and their q^2 dependence compared to the VMD model in Fig. 9. Single off-shell form factors can be studied in:

1. pseudoscalar meson decays $P \rightarrow l^+ l^- \gamma$ ($4m_l^2 < q^2 < m_P^2$);
2. $e^+ e^- \rightarrow P \gamma$ ($q^2 > m_P^2$), where the cross section is given by

$$\sigma(e^+ e^- \rightarrow P \gamma) = 4\pi\alpha_{\text{QED}}\Gamma_{\gamma\gamma} \left(\frac{s - m_P^2}{sm_P} \right)^3 |F_P(q^2 = s, 0)|^2; \quad (9)$$

3. two-photon production: e.g., in $e^- e^\pm$ interactions or the Primakoff process ($q^2 < 0$)

$$\sigma_{\gamma^* \gamma^* \rightarrow P} = \frac{16\pi^2}{m_P^3} \Gamma_{\gamma\gamma} |F(q_1^2, q_2^2)|^2 \sqrt{(q_1 \cdot q_2)^2 - q_1^2 q_2^2} \delta((q_1 + q_2)^2 - m_P^2). \quad (10)$$

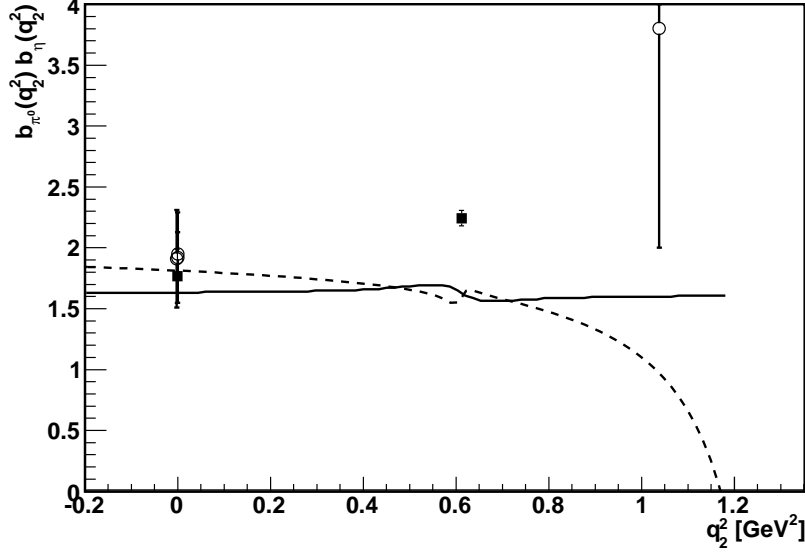


Figure 9: Slopes $b_{\pi^0}(q_2^2)$ and $b_{\eta}(q_2^2)$ in naive VMD (solid and dashed lines, respectively), compared to experimental data from Table 6 (filled squares and open circles, respectively).

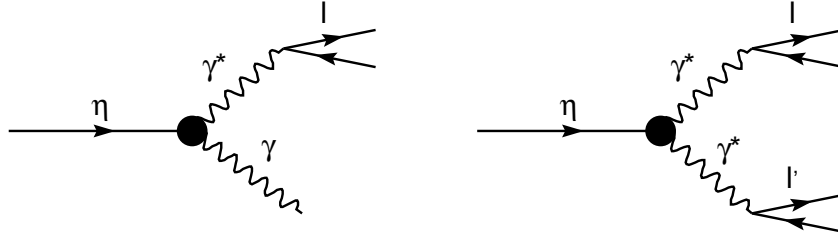


Figure 10: Single and double Dalitz decays

1.3 Dalitz decays

The $q_{1,2}^2$ for the conversion (Dalitz) decays, see Fig. 10, is equal to the invariant mass squared of the lepton-antilepton pair, and $m_P^2 \geq q_{1,2}^2 \geq 4m_\ell^2$ (time-like virtual photons). The amplitude of the single conversion decay of a pseudoscalar meson P is given by

$$\mathcal{A}(P \rightarrow \ell^+ \ell^- \gamma) = ie\mathcal{F}_P(q_1^2, 0)\epsilon_{\mu\nu\sigma\tau}\epsilon_2^\mu q_2^\nu \epsilon_1^\sigma \frac{1}{q_1^2} [\bar{u}\gamma^\tau u], \quad (11)$$

where $1/q_1^2$ is the photon propagator and the last term is the leptonic current.

Experimentally, the form factor can be extracted from the $q^2 = q_1^2$ distribution given by

$$\frac{d\Gamma(P \rightarrow \ell^+ \ell^- \gamma)}{dq^2 \Gamma_{\gamma\gamma}} = \frac{2\alpha}{3\pi} \frac{1}{q^2} \sqrt{1 - \frac{4m_\ell^2}{q^2}} \left(1 + \frac{2m_\ell^2}{q^2}\right) \left(1 - \frac{q^2}{M_P^2}\right)^3 |F_P(q^2, 0)|^2. \quad (12)$$

The distributions for η Dalitz decays are presented in Fig. 11. The distributions for the $e^+e^-\gamma$ final states are peaked at $4m_\ell^2$ due to the $1/q^2$ QED term. The form factor can be obtained by dividing out the QED dependence. To extract the form factor slope, a

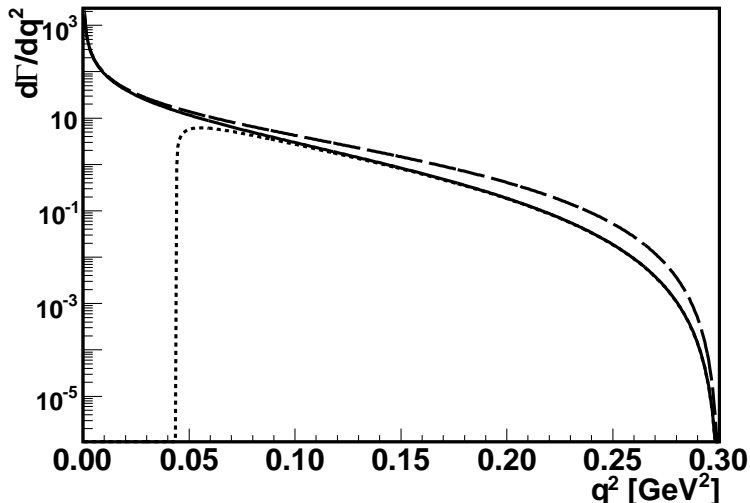


Figure 11: $d\Gamma/dq^2$ distributions for the single Dalitz decays of the η meson. The solid line corresponds to $\eta \rightarrow e^+e^-\gamma$ with $F_\eta(q^2, 0) = 1$; the dotted line shows $\eta \rightarrow \mu^+\mu^-\gamma$ with $F_\eta(q^2) = 1$; finally, the dashed line is $\eta \rightarrow e^+e^-\gamma$ with the VMD form factor, see Sect. 1.5.

dependence on the q^2 variable is often fitted with a single-pole formula, which at low energies $q^2 \ll \Lambda^2$ can be approximated successively as follows:

$$F(q^2, 0) = \frac{\Lambda^2}{\Lambda^2 - q^2 - i\Gamma\Lambda} \approx \frac{\Lambda^2}{\Lambda^2 - q^2} \approx 1 + \frac{q^2}{\Lambda^2}. \quad (13)$$

The form factor slope $b_P(0)$ is therefore related to Λ :

$$b_P(0) \equiv \left. \frac{d \ln F(q^2, 0)}{dq^2} \right|_{q^2=0} = \frac{1}{\Lambda^2}. \quad (14)$$

1.4 Radiative and hadronic anomalous processes

Finally, there is one more twist: the ρ meson is rather broad and couples to two pions. Therefore processes that involve two pions instead of a dilepton are also intimately connected to the previous reactions. This includes, e.g., $\eta \rightarrow \pi^+\pi^-\gamma^{(*)}$. There are indications for deviations from vector-meson dominance [60–62]. (Of course, this logic can be extended to reactions with three pions instead of an ω or ϕ . In these cases, however, there are a lot of different channels interfering with each other.) — A list of possible reactions thus related to each other is provided in Appendix 1.A.

1.5 A naive Vector Meson Dominance model picture

For some processes, model-independent analyses using dispersion theory are possible; for recent developments, see e.g. Ref. [51, 63]. Symmetry constraints may be invoked using properly-chosen matching conditions, say, to chiral perturbation theory [62]. However here, for illustration, only predictions of the most naive VMD model (photon couplings *solely*

through vector mesons) will be presented in some detail. The transition form factor of a pseudoscalar meson $P(\pi^0, \eta, \eta')$ is given within the model by [6, 64, 65]:

$$F_P^{\text{VMD}}(q_1^2, q_2^2) = \frac{1}{N} \sum_V \sum_{V'} \frac{g_{PVV'}}{g_{V\gamma} g_{V'\gamma}} \frac{D_V(0)}{D_V(q_1^2)} \frac{D_{V'}(0)}{D_{V'}(q_2^2)}. \quad (15)$$

The sum extends over the neutral vector mesons ($Q = S = 0$): $\rho^0, \omega, \phi, \dots$; $g_{PVV'}$ and $g_{V\gamma}$ are their flavor SU(3) couplings to the pseudoscalar meson P and to the photon, respectively. The functions $D_V(q^2)$ are vector meson propagators, where for illustration we use the simplest expression defined in the whole (real) q^2 range:

$$D_V(q^2) = M_V^2 - q^2 - i\Gamma_V M_V \quad (16)$$

with constant vector meson widths Γ_V . $D_V(0)$ is approximately M_V^2 as long as the width is considered small.

In the following, we keep only the three lightest vector mesons in the sum and take the values of the couplings $g_{\eta V V}$ and $g_{V\gamma}$ as expected from the quark model; moreover, the η has been assumed to be a pure flavor-octet state for simplicity:

$$\frac{1}{2g_{\rho\gamma}} : \frac{1}{2g_{\omega\gamma}} : \frac{1}{2g_{\phi\gamma}} = 1 : \frac{1}{3} : -\frac{\sqrt{2}}{3}, \quad g_{\eta\rho\rho} : g_{\eta\omega\omega} : g_{\eta\phi\phi} = 1 : 1 : -2. \quad (17)$$

These factors are obtained in the following way: using the meson multiplets

$$P = \begin{pmatrix} \pi^0 + \frac{1}{\sqrt{3}}\eta & \sqrt{2}\pi^+ & \sqrt{2}K^+ \\ \sqrt{2}\pi^- & -\pi^0 + \frac{1}{\sqrt{3}}\eta & \sqrt{2}K^0 \\ \sqrt{2}K^- & \sqrt{2}\bar{K}^0 & -\frac{2}{\sqrt{3}}\eta \end{pmatrix}, \quad V = \begin{pmatrix} \rho^0 + \omega & \sqrt{2}\rho^+ & \sqrt{2}K^{*+} \\ \sqrt{2}\rho^- & -\rho^0 + \omega & \sqrt{2}K^{*0} \\ \sqrt{2}K^{*-} & \sqrt{2}\bar{K}^{*0} & \sqrt{2}\phi \end{pmatrix}, \quad (18)$$

and the quark-charge matrix

$$Q = \begin{pmatrix} \frac{2}{3} & 0 & 0 \\ 0 & -\frac{1}{3} & 0 \\ 0 & 0 & -\frac{1}{3} \end{pmatrix}, \quad (19)$$

one obtains the photon coupling ratios from the flavor trace $\text{tr}\{V Q\}$ and the PVV couplings from $\text{tr}\{(V_1 V_2 + V_2 V_1) P\}$. The normalization factor N ensures that $F_P^{\text{VMD}}(0, 0) = 1$. For π^0 and η , due to isospin conservation and the OZI rule one finds the following expressions:

$$F_{\pi^0}^{\text{VMD}}(q_1^2, q_2^2) = \frac{1}{2} \left\{ \frac{D_\rho(0)}{D_\rho(q_1^2)} \frac{D_\omega(0)}{D_\omega(q_2^2)} + \frac{D_\omega(0)}{D_\omega(q_1^2)} \frac{D_\rho(0)}{D_\rho(q_2^2)} \right\}, \quad (20)$$

$$F_\eta^{\text{VMD}}(q_1^2, q_2^2) = \frac{1}{N} \left\{ \frac{g_{\eta\rho\rho}}{g_{\rho\gamma}^2} \frac{D_\rho(0)}{D_\rho(q_1^2)} \frac{D_\rho(0)}{D_\rho(q_2^2)} + \frac{g_{\eta\omega\omega}}{g_{\omega\gamma}^2} \frac{D_\omega(0)}{D_\omega(q_1^2)} \frac{D_\omega(0)}{D_\omega(q_2^2)} + \frac{g_{\eta\phi\phi}}{g_{\phi\gamma}^2} \frac{D_\phi(0)}{D_\phi(q_1^2)} \frac{D_\phi(0)}{D_\phi(q_2^2)} \right\}.$$

In Fig. 12 the resulting squares of the absolute values of the form factors are drawn for π^0 and η . There are three experimentally accessible regions of the form factors. The boundaries are defined by the parabola and the axes of the plots. The region inside the parabola and inside the second and fourth quarters of the diagrams are not accessible experimentally.

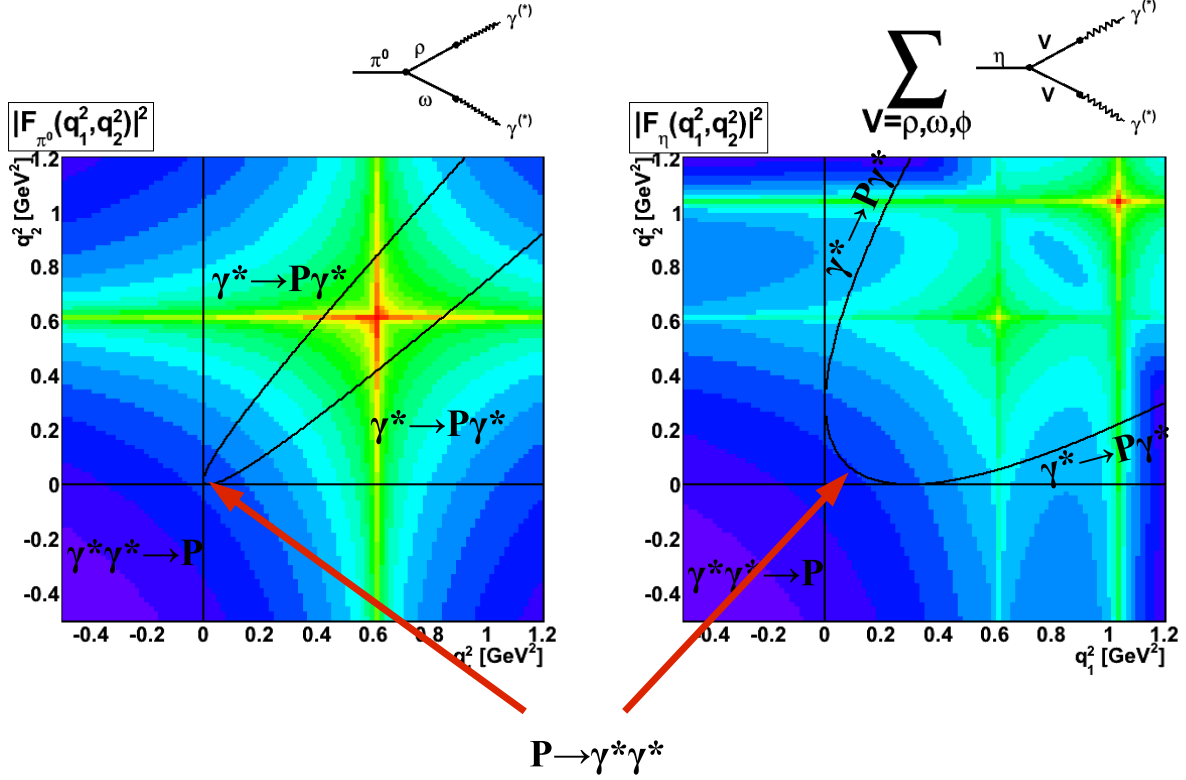


Figure 12: The π^0 and η meson form factor squared in naive VMD.

The $P \rightarrow \gamma^{(*)}\gamma^{(*)}$ decays will probe the central region of the plot defined by the conditions: $q_{1,2}^2 \geq 0$ and $\sqrt{q_1^2} + \sqrt{q_2^2} \leq m_P$. Processes $e^+e^- \rightarrow P\gamma^{(*)}$ correspond to: $\sqrt{q_1^2} > m_P$, $0 \leq \sqrt{q_2^2} \leq \sqrt{q_1^2} - m_P$. Finally, $\gamma^{(*)}\gamma^{(*)} \rightarrow P$ processes (from e^+e^- collisions) allow to study the whole $q_1^2, q_2^2 \leq 0$ region.

In particular, for a single on-shell photon the form factor reduces to the formula from Ref. [6]:

$$F_P^{\text{VMD}}(q^2, 0) = \frac{1}{N} \sum_V \frac{g_{PV\gamma}}{2g_{V\gamma}} \frac{D_V(0)}{D_V(q^2)} \approx \frac{1}{N} \sum_V \frac{g_{PV\gamma}}{2g_{V\gamma}} \frac{M_V^2}{D_V(q^2)}, \quad (21)$$

where

$$g_{PV\gamma} = \sum_{V'} \frac{g_{PVV'}}{g_{V'\gamma}}. \quad (22)$$

Appendix

1.A List of processes

Here, we compile a list of reactions that are relevant and linked to each other in the context of transition form factors. The focus is on reactions that are possible to study in practice. For example, scattering reactions with initial-state neutral pions (like $\pi^0\gamma \rightarrow \text{something}$) are not considered because there are no π^0 beams available. There is a charged-pion beam, though (COMPASS at CERN), and “collisions” with photons can be achieved using the

Primakoff effect. Likewise, reactions with initial-state muons are not listed, though this is one of the future dreams of high-energy physicists. Reactions that involve a broad ρ meson are listed in the following as $\pi^+\pi^-$. In principle, reactions like $e^+e^- \rightarrow \pi^+\pi^-$ and $e^+e^- \rightarrow \pi^0\omega$ are related to $\tau^- \rightarrow \nu_\tau \pi^- \pi^0$ and $\tau^- \rightarrow \nu_\tau \pi^- \omega$ through conservation of vector current and isospin symmetry [66]. Decays of the τ are not listed below.

1. Processes with one external (pseudoscalar) hadron: π^0

- | | |
|---------------------------------------|---|
| (a) $\pi^0 \rightarrow 2\gamma$ | (e) $e^+e^- \rightarrow \pi^0 \gamma$ |
| (b) $\pi^0 \rightarrow \gamma e^+e^-$ | (f) $e^+e^- \rightarrow \pi^0 e^+e^-$ |
| (c) $\pi^0 \rightarrow e^+e^- e^+e^-$ | (g) $e^+e^- \rightarrow \pi^0 \mu^+\mu^-$ |
| (d) $\pi^0 \rightarrow e^+e^-$ | |

2. Processes with one external (pseudoscalar) hadron: η

- | | |
|--|--|
| (a) $\eta \rightarrow 2\gamma$ | (g) $\eta \rightarrow e^+e^-$ |
| (b) $\eta \rightarrow \gamma e^+e^-$ | (h) $\eta \rightarrow \mu^+\mu^-$ |
| (c) $\eta \rightarrow \gamma \mu^+\mu^-$ | (i) $e^+e^- \rightarrow \eta \gamma$ |
| (d) $\eta \rightarrow e^+e^- e^+e^-$ | (j) $e^+e^- \rightarrow \eta e^+e^-$ |
| (e) $\eta \rightarrow e^+e^- \mu^+\mu^-$ | (k) $e^+e^- \rightarrow \eta \mu^+\mu^-$ |
| (f) $\eta \rightarrow \mu^+\mu^- \mu^+\mu^-$ | |

3. Processes with one external (pseudoscalar) hadron: η'

- | | |
|---|---|
| (a) $\eta' \rightarrow 2\gamma$ | (g) $\eta' \rightarrow e^+e^-$ |
| (b) $\eta' \rightarrow \gamma e^+e^-$ | (h) $\eta' \rightarrow \mu^+\mu^-$ |
| (c) $\eta' \rightarrow \gamma \mu^+\mu^-$ | (i) $e^+e^- \rightarrow \eta' \gamma$ |
| (d) $\eta' \rightarrow e^+e^- e^+e^-$ | (j) $e^+e^- \rightarrow \eta' e^+e^-$ |
| (e) $\eta' \rightarrow e^+e^- \mu^+\mu^-$ | (k) $e^+e^- \rightarrow \eta' \mu^+\mu^-$ |
| (f) $\eta' \rightarrow \mu^+\mu^- \mu^+\mu^-$ | |

4. Processes with two external (narrow) hadrons: π^0 and a vector meson

- | | |
|---|---|
| (a) $\omega \rightarrow \pi^0 \gamma$ | (e) $\phi \rightarrow \pi^0 \gamma$ |
| (b) $\omega \rightarrow \pi^0 e^+e^-$ | (f) $\phi \rightarrow \pi^0 e^+e^-$ |
| (c) $\omega \rightarrow \pi^0 \mu^+\mu^-$ | (g) $\phi \rightarrow \pi^0 \mu^+\mu^-$ |
| (d) $e^+e^- \rightarrow \omega \pi^0$ | (h) $e^+e^- \rightarrow \phi \pi^0$ |

5. Processes with two external (narrow) hadrons: η and a vector meson

- | | |
|---|---|
| (a) $\omega \rightarrow \eta \gamma$ | (e) $\phi \rightarrow \eta \gamma$ |
| (b) $\omega \rightarrow \eta e^+ e^-$ | (f) $\phi \rightarrow \eta e^+ e^-$ |
| (c) $\omega \rightarrow \eta \mu^+ \mu^-$ | (g) $\phi \rightarrow \eta \mu^+ \mu^-$ |
| (d) $e^+ e^- \rightarrow \omega \eta$ | (h) $e^+ e^- \rightarrow \phi \eta$ |

6. Processes with two external (narrow) hadrons: η' and a vector meson

- | | |
|--|--------------------------------------|
| (a) $\eta' \rightarrow \omega \gamma$ | (d) $\phi \rightarrow \eta' \gamma$ |
| (b) $\eta' \rightarrow \omega e^+ e^-$ | (e) $\phi \rightarrow \eta' e^+ e^-$ |
| (c) $e^+ e^- \rightarrow \omega \eta'$ | (f) $e^+ e^- \rightarrow \phi \eta'$ |

7. Processes with three external (pseudoscalar) hadrons: $\pi^0 \pi^+ \pi^-$

- | | |
|--|---|
| (a) $\pi^\pm \gamma \rightarrow \pi^0 \pi^\pm$ | (b) $e^+ e^- \rightarrow \pi^0 \pi^+ \pi^-$ |
|--|---|

8. Processes with three external (pseudoscalar) hadrons: $\eta \pi^+ \pi^-$

- | | |
|--|---|
| (a) $\eta \rightarrow \pi^+ \pi^- \gamma$ | (d) $\pi^\pm \gamma \rightarrow \eta \pi^\pm$ |
| (b) $\eta \rightarrow \pi^+ \pi^- e^+ e^-$ | (e) $e^+ e^- \rightarrow \eta \pi^+ \pi^-$ |
| (c) $\eta \rightarrow \pi^+ \pi^- \mu^+ \mu^-$ | |

9. Processes with three external (pseudoscalar) hadrons: $\eta' \pi^+ \pi^-$

- | | |
|---|--|
| (a) $\eta' \rightarrow \pi^+ \pi^- \gamma$ | (d) $\pi^\pm \gamma \rightarrow \eta' \pi^\pm$ |
| (b) $\eta' \rightarrow \pi^+ \pi^- e^+ e^-$ | (e) $e^+ e^- \rightarrow \eta' \pi^+ \pi^-$ |
| (c) $\eta' \rightarrow \pi^+ \pi^- \mu^+ \mu^-$ | |

Note that the coupling of three neutral pseudoscalars to a photon breaks charge-conjugation invariance. In principle, one could add processes with more external hadrons to the list, e.g., $\eta' \rightarrow \pi^+ \pi^- \pi^+ \pi^-$ and $\eta' \rightarrow \pi^+ \pi^0 \pi^- \pi^0$, which could proceed via two virtual ρ mesons. For a theoretical discussion of these decays, see Ref. [67]. The list above is restricted to four or less external states, but counting a virtual photon as one state.

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2 Short summaries of the talks

2.1 Muon $g - 2$ from τ and e^+e^- data

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The leading hadronic contribution to the very precisely measured muon $g - 2$ [1] is obtained most reliably by using a dispersion relation together with $e^+e^- \rightarrow$ hadrons data. As a drawback, the precision of the theoretical prediction of the muon anomaly a_μ is dominated by experimental errors. The dominant contribution is coming from the $\pi^+\pi^-$ channel at low energies. More data help to improve the precision of the prediction. The hadronic final states in the reactions $e^+e^- \rightarrow \pi^+\pi^-$ and $\tau^- \rightarrow \nu_\tau \pi^- \pi^0$ are related by isospin symmetry, up to isospin breaking (IB) effects due to $m_d \neq m_u$ and differently charged particles involved. After an isospin rotation and IB-corrections one thus can use the high quality τ -decay spectra to enhance the data set needed for evaluating a_μ^{had} [2]. As more data and data of better quality got available, a serious clash showed up between τ - and e^+e^- -data [3]. Recently, in Ref. [4], the τ vs. e^+e^- puzzle has been resolved. The discrepancy turned out to be due to so far unaccounted self-energy corrections in $\rho^0 - \gamma$ mixing. It contributes to $e^+e^- \rightarrow \pi^+\pi^-$, but is absent in τ -decays. After correcting the τ -data for the missing $\rho - \gamma$ mixing, besides the other known IB-corrections, the I=1 $\pi\pi$ results are fully compatible. τ -data thus confirm e^+e^- -based a_μ^{had} evaluations. For the leading-order vacuum polarization contribution, based on all e^+e^- data (CMD2, SND, KLOE and BaBar), we obtain $a_\mu^{\text{had,LO}}[e] = 690.75(4.72) \times 10^{-10}$ (e^+e^- based), while including τ data (ALEPH, OPAL, CLEO and Belle) we find $a_\mu^{\text{had,LO}}[e, \tau] = 690.96(4.65) \times 10^{-10}$ ($e^+e^- + \tau$ based). This backs the $\sim 3\sigma$ deviation between $a_\mu^{\text{experiment}}$ and a_μ^{theory} . For the τ di-pion branching fraction we find $B_{\pi\pi^0}^{\text{CVC}} = 25.20 \pm 0.17 \pm 0.28$ from $e^+e^- + \text{CVC}$, while $B_{\pi\pi^0} = 25.34 \pm 0.06 \pm 0.08$ is evaluated directly from the τ spectra. Applying our correction to the most recent evaluation [5] we have

$a_\mu^{2\pi, \text{LO}}[E < 1.8 \text{ GeV}]$	a_μ^{the}	$a_\mu^{\text{exp}} - a_\mu^{\text{the}}$		
(514.1 ± 3.8)	11659186.5(5.4)	(22.4 ± 8.3)	2.7σ	[BaBar]
(507.8 ± 3.2)	11659180.2(5.0)	(28.7 ± 8.0)	3.6σ	[ee all]
(508.7 ± 2.5)	11659181.1(4.6)	(27.8 ± 7.8)	3.6σ	[$ee + \tau$]

(in units 10^{-10}) where the last entry is our estimate combining ee and τ results (see also [6]).

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2.2 A lattice study of the leading order hadronic contribution to the muon anomalous magnetic moment

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We present a calculation of the leading order hadronic contribution to the muon anomalous magnetic moment a_μ^{had} from lattice QCD computations based on first principles. We report about a first benchmark calculation with mass-degenerate up and down quarks using the ETMC configurations [1]. Using maximally twisted mass fermions as our formulation of lattice QCD guarantees that physical observables are automatically accurate to $O(a^2)$ in the lattice spacing, allowing therefore a well controlled continuum limit. By employing an improved definition of the lattice observable for a_μ^{had} [2, 3] we can achieve an accuracy of a_μ^{had} that is almost matching the experimental precision. Using this improved method allows us to also accurately compute the hadronic contribution to $\Delta\alpha_{\text{QED}}$, the Adler function and muonic atoms, see [3]. Since ETMC has by now also calculations with a dynamical strange and charm quark[4], we have also performed a first ever four-flavor calculation of a_μ^{had} finding consistent values with phenomenological standard model calculations.

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2.3 Confronting the scan, ISR and tau dipion spectra within a global model

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The Hidden Local Symmetry (HLS) Model [1] has given rise to successful phenomenological studies once a mechanism accounting for the breaking of the SU(3) and SU(2) symmetries has been performed. An additional mechanism has been implemented which performs the mixing of the vector mesons ρ^0 , ω and ϕ ; this vector meson mixing plays a fundamental role in generating the coupling of the ω and ϕ mesons to a pion pair. Within this framework (which can be found in detail in Ref.[2]), it is possible to treat consistently and *simultaneously* the annihilation channels $e^+e^- \rightarrow \pi^+\pi^-/K^+K^-/K^0\bar{K}^0/\pi^0\gamma/\eta\gamma/\pi^+\pi^-\pi^0$, the $\tau^\pm \rightarrow \pi^\pm\pi^0\nu_\tau$ decay spectrum and some additional decay partial widths. Using almost all the relevant existing data sets collected in scan experiments and the ALEPH, CLEO and BELLE τ spectra, one has reached a surprisingly good accuracy as illustrated in [2, 3].

We have presented an update of the analysis reported in Ref. [2] by examining the behavior of the $e^+e^- \rightarrow \pi^+\pi^-$ spectra collected at the VEPP2M e^+e^- collider by the scan procedure and those collected by KLOE (referred to as KLOE08 and KLOE10) and also by BaBar using the Initial State Radiation (ISR) method. The tool for this comparison is a global fit including the three τ spectra already mentioned together with all data referred to above (excluding $e^+e^- \rightarrow \pi^+\pi^-$). However, this is not sufficiently precise and using some more information (essentially the $\rho^0 \rightarrow e^+e^-$ partial width, marginally present in the other channels considered, and the $\omega/\phi \rightarrow \pi^+\pi^-$ partial widths), it has been possible to show that the $e^+e^- \rightarrow \pi^+\pi^-$ cross sections from CMD-2, SND and KLOE10 are perfectly consistent with each other and with all the other (non- $\pi^+\pi^-$) data considered.

We have shown that this (reference) merged data set (CMD-2, SND and KLOE10) introduced within the global fit code leads to a value for the muon $g - 2$ which is at about 4.5σ from the BNL measurement [4]. The returned global fit quality is above the 90% level. On the other hand, using some weighting, the KLOE08 and BaBar data sets have also been considered within the global fit; this has confirmed the above mentioned result for the muon $g - 2$.

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2.4 Light Meson Decays with WASA-at-COSY

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The meson decay physics program with the WASA detector at the COSY accelerator pursues symmetry breaking processes by studying rare decays of the light unflavored mesons as well as the determination of electromagnetic transition form factors. The experimental approach uses the WASA facility which is a 4π detector system, designed to study the hadronic production and the decays of light mesons with the decay products γ, π, e^\pm . The unique high density pellet target combined with high intensity beams of the Cooler Synchrotron COSY, Jülich, provide luminosities which allow studies of rare processes [1].

The three-pion decays of η and ω mesons hold important information for chiral perturbation theory and the promise to extract limits on the quark mass differences. For the η decay into three neutral pions, the Dalitz plot of the three pions was studied and the quadratic slope parameter α was determined to be $-0.027 \pm 0.008(stat) \pm 0.005(syst)$. The result is consistent with previous measurements and further corroborates the importance of pion-pion final state interactions [2]. Using our extended data set on η decays as well as recently acquired data on ω decays, we continue the Dalitz plot analyses for the case of $\pi^+\pi^-\pi^0$ in the final state [3, 4].

Decays of the π^0 meson allow to search for gauge bosons mediating dark forces in the MeV range. The decay $\pi^0 \rightarrow ee\gamma$ is sensitive to a “dark photon” that decays into an e^+e^- pair. WASA-at-COSY has collected a 500k data sample to constrain the parameters of this hypothetical gauge boson [5]. The rare decay $\pi^0 \rightarrow ee$ could probe physics beyond the Standard Model. Deviations between experiment and the Standard Model prediction would be explained by a dark gauge boson, which might also account for the enhanced e^+e^- annihilation line from the galactic center. The upcoming high statistics run with WASA-at-COSY could confirm the present experimental result.

We have performed an exclusive measurement of the decay $\eta \rightarrow \pi^+\pi^-\gamma$. At the chiral limit of zero momentum and massless quarks this decay is determined by the box anomaly term of the Wess–Zumino–Witten Lagrangian. The measured pion angular distribution is consistent with a relative p-wave of the two-pion system, whereas the measured photon energy spectrum was found at variance with the simplest gauge invariant matrix element. A parameterization of the data can be achieved by the additional inclusion of the empirical pion vector form factor multiplied by a first-order polynomial in the squared invariant mass of the $\pi\pi$ system [6].

We report on our efforts to determine transition form factors using the decays $\eta \rightarrow \gamma^{(*)}ee$ and $\omega \rightarrow \pi ee$. For the status and preliminary results on transition form factors, we present preliminary results for the η transition form factor from the decays $\eta \rightarrow \gamma ee$. The results are based on two independent analyses using two different production mechanisms [7, 8]. We point out further steps towards our final result, expected at the end of 2012. The decay $\eta \rightarrow eeee$ carries information about the double transition form factor and is being studied with the first goal of a branching ratio [4, 9]. ω decays are being analyzed using a four-week

$pd \rightarrow {}^3\text{He}\omega$ experiment and a one-week $p + p$ pilot run. As a first step towards the $\omega\pi$ transition form factor, we study the decay with a real photon, $\omega \rightarrow \pi\gamma$. Promising first results show the ω peak in a missing mass analysis, inclusively and in the presence of the respective decay products [3, 4].

In summary, we have accumulated 3×10^7 η mesons produced in $pd \rightarrow {}^3\text{He}\eta$ and $5\text{--}10 \times 10^8$ η decays in $pp \rightarrow pp\eta$. The experimental goal is to study very rare meson decays like $\eta \rightarrow ee$. The current studies of ω decays focus on two pilot experiments and will develop the experimental and analysis methods to process a planned high-statistics experiment to take place before 2015. The goal is a precise determination of the $\omega\pi$ transition form factor.

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2.5 Recent results and perspectives on pseudoscalar mesons and form factors at BES III

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The BES III experiment [1] is located at IHEP in Beijing (China). It is an e^+e^- collider collecting data in a center-of-mass energy range within $[2.0 \div 4.6]$ GeV. The physics program of this project is wide and ambitious, mainly devoted to the light hadron spectroscopy. With its recent 1 billion J/ψ collected and 2.9 fb^{-1} integrated luminosity data collected at the $\psi(3770)$ energy, the BES III project offers a unique opportunity to perform spectroscopy studies and measurements of transition form factors. The decay of η and η' have been right now under investigation in this project.

$\eta - \eta'$ mixing probes the strange quark content of light pseudoscalar mesons and gluon dynamics of QCD. Hadronic decays of η' have garnered attention, in particular those to 3 pions, because they can probe isospin symmetry breaking. The contribution of BES III in this sector has been:

1. a measurement of the branching fraction (BF) of the decay $\eta' \rightarrow \eta\pi^+\pi^-$ and extrapolation of the Dalitz plot parameters, using a 225 million J/ψ data sample [2]. The hadronic decay of η' is extremely valuable in studies devoted to the effect of the gluon component in chiral perturbation theory and the possible nonet of light scalars. The conclusion of this recent BES III publication is that the two parameterizations used to parameterize the amplitude distribution (named *general decomposition* and *linear parameterization*) [3] are not equivalent, as expected. However, the parameter related to probe C -parity violation in this strong decay in both parameterizations is consistent with 0;
2. a preliminary study has been started in BES III to calculate the $\text{BF}(\eta' \rightarrow \pi^+\pi^-l^+l^-)$, where $l = e, \mu$. Theoretical predictions make the decay $\eta' \rightarrow \pi^+\pi^-e^+e^-$ extremely more probable than $\eta' \rightarrow \pi^+\pi^-\mu^+\mu^-$. BES III can now confirm the theoretical expectation and the results from previous experiments [4];
3. a measurement of the transition form factors in the decay $e^+e^- \rightarrow e^+e^-\pi^0/\eta/\eta'$ via $\gamma\gamma$ interactions has been started. The sample used for such a study is the data sample collected from BES III at $\psi(3770)$. Feasibility studies show that these analyses are feasible in the range of the transfer momentum Q^2 within $[0.3 \div 10]$ GeV². The BES III data are going to be in part complementary to the data already published from other experiments [5–8] and they are sensitive to the best range for the hadronic light-by-light correction to the measurement of the muon anomaly $(g-2)_\mu$, which is supposed to be determined in $[0.2 \div 1.5]$ GeV² [9, 10]. In fact, the main motivation to perform this analysis is the precise measurement of $(g-2)_\mu$, as it was found to be by 3.6σ deviated from the Standard Model expectation. The light-by-light hadronic correction to this measurement are essential for a precise determination of $(g-2)_\mu$ and test the Standard Model at low energy scale.

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2.6 Measurements of the photon-meson transition form factors

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A review of the BABAR measurements [1–3] of the photon-meson transition form factors for the light pseudoscalar mesons π^0 , η , and η' is presented. The recent Belle measurement [4] of the $\gamma^*\gamma \rightarrow \pi^0$ form factor is discussed and compared with the BABAR result. Belle has about two times larger systematic uncertainty ($\sim 10\%$ at $Q^2 = 10 \text{ GeV}^2$). The difference between BABAR and Belle measurements is about two systematic errors.

Further measurements of the photon-meson transition form factors in existing and future experiments are discussed. In particular, the transition form factor as a function of q^2 's of both photons can be measured using BABAR data for the η' . Plans of the two-photon single-tag measurements at VEPP-2000 at relatively low Q^2 from 0.05 to 0.6 GeV^2 are presented.

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2.7 Measurement of $\gamma\gamma^* \rightarrow \pi^0$ transition form factor at Belle

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We report a measurement of the process $\gamma\gamma^* \rightarrow \pi^0$ with a 759 fb^{-1} data sample [1] recorded with the Belle detector [2] at the KEKB asymmetric-energy e^+e^- collider [3]. The pion transition form factor, $F(Q^2)$, is measured for the kinematical region $4 \text{ GeV}^2 \lesssim Q^2 \lesssim 40 \text{ GeV}^2$, where $-Q^2$ is the invariant mass squared of a virtual photon.

Production of a neutral pion in the single-tag two-photon process $e^+e^- \rightarrow (e)e\pi^0$, where e and (e) in the final state are a tagged and an untagged electron, respectively, is measured, and the differential cross section in Q^2 is converted to the transition form factor [4, 5]. A Bhabha-veto logic in our hardware trigger system [6] induces a significant efficiency loss in collecting the signal events. We have calibrated and tuned the effect in our Monte-Carlo simulator, using both data and Monte-Carlo samples from the radiative-Bhabha process with the virtual-Compton scattering configuration [7].

The measured values of $Q^2|F(Q^2)|$ agree with the previous measurements [5, 8, 9] for $Q^2 \lesssim 9 \text{ GeV}^2$. In the higher Q^2 region, in contrast to BaBar, our results do not show a rapid growth with Q^2 and are closer to theoretical expectations [10, 11], as shown in Fig. 13.

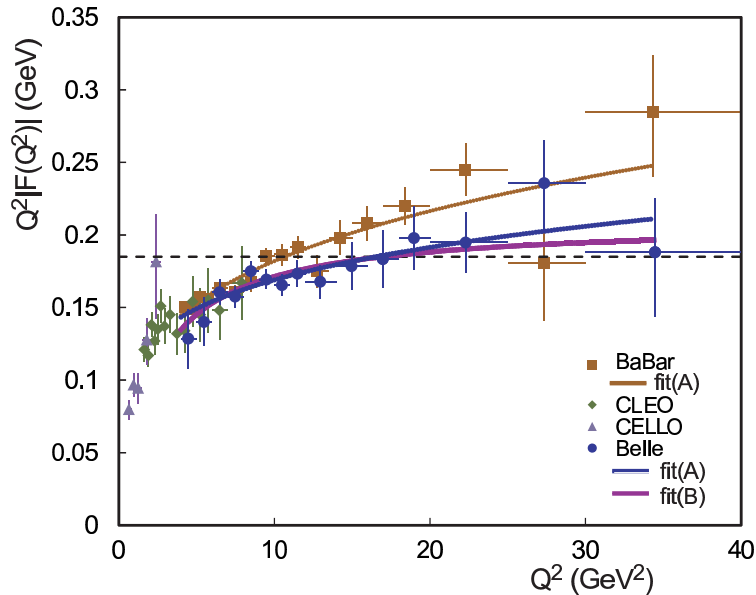


Figure 13: Comparison of the results for the product $Q^2|F(Q^2)|$ for the π^0 from different experiments [1, 5, 8, 9]. The error bars are a quadratic sum of statistical and systematic uncertainties. For the Belle and BaBar results, only a Q^2 -dependent systematic-error component is included. The two curves denoted fit(A) use the BaBar parameterization, $\sim (Q^2/10 \text{ GeV}^2)^\beta$, while the curve denoted fit(B) uses $\sim Q^2/(Q^2 + C)$ [1]. The dashed line shows the asymptotic prediction from pQCD ($\sim 0.185 \text{ GeV}$).

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2.8 Form factors and hadronic contributions to $(g - 2)_\mu$ from Dyson-Schwinger equations

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We review results on form factors in the Dyson-Schwinger approach and discuss recent applications to the problem of hadronic contributions to $(g - 2)_\mu$. Based on a model for the quark-gluon interaction, the approach is capable to reproduce experimental results on static and dynamic electromagnetic properties of light mesons at the level of five to ten percent. Well within this error we are also able to reproduce the result for hadronic vacuum polarization contributions extracted from experiment via dispersion relations [1]. Our results are in good agreement with corresponding lattice calculations at several quark masses and number of active flavors. We discuss the application of our approach to the much debated hadronic light-by-light scattering contribution to $(g - 2)_\mu$ and present our latest results [2–4]. We also compare our framework with the corresponding model approaches [4].

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2.9 Hadronic contribution to $(g - 2)_\mu$ from e^+e^- annihilations and τ decays

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A reevaluation of the hadronic contributions to the muon magnetic anomaly is presented. It includes the latest $\pi^+\pi^-$ cross-section data from the KLOE experiment, all available data from BABAR, an estimation of missing low-energy contributions using results on cross sections and process dynamics from BABAR, and an evaluation of the continuum contributions from perturbative QCD at four-loop order. The evaluation of all experimental contributions including an analysis of inter-experiment and inter-channel correlations is performed with the software package HVPTools. The new estimate features a decrease in the hadronic contribution with respect to earlier evaluations. We find that the full Standard Model prediction of the muon $g - 2$ differs from the experimental value by 3.6σ (2.4σ) for the e^+e^- -based (τ -based) analysis. Also presented is a preliminary determination of $R_{e^+e^- \rightarrow \text{hadrons}}$ versus the center-of-mass energy including a full evaluation of energy-dependent uncertainties and correlations. Details on the results presented can be found in Ref. [1–3].

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2.10 Hadronic light-by-light scattering in the muon $g - 2$: impact of transition form factor measurements

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The calculation of the hadronic light-by-light (had. LbyL) scattering contribution to the muon $g - 2$ currently relies entirely on models. Measurements of the form factors which describe the interactions of hadrons with photons can constrain the models and reduce the uncertainty in $a_\mu^{\text{had. LbyL}} = (116 \pm 40) \times 10^{-11}$ [1]. Recently it was found in Ref. [2] that the KLOE-2 experiment, within one year of data taking, could measure the decay width $\Gamma_{\pi^0 \rightarrow \gamma\gamma}$ to 1% statistical precision and the transition form factor $\mathcal{F}_{\pi^0\gamma^*\gamma}(Q^2)$ for small space-like momenta, $0.01 \text{ GeV}^2 < Q^2 < 0.1 \text{ GeV}^2$, to 6% statistical precision in each bin. The impact of these measurements on estimates of the dominant pion-exchange contribution to $a_\mu^{\text{had. LbyL}}$ was also discussed in Ref. [2].

In the pion-exchange contribution, the form factor $\mathcal{F}_{\pi^0\gamma^*\gamma^*}((q_1 + q_2)^2, q_1^2, q_2^2)$ with an off-shell pion with momentum $(q_1 + q_2)$ enters, see Ref. [1] and references therein for more details. In general, measurements of the transition form factor $\mathcal{F}_{\pi^0\gamma^*\gamma}(Q^2) \equiv \mathcal{F}_{\pi^0\gamma^*\gamma^*}(m_\pi^2, -Q^2, 0)$ are only sensitive to a subset of the model parameters. Thus, having a good description for $\mathcal{F}_{\pi^0\gamma^*\gamma}(Q^2)$ is only necessary, not sufficient, to determine $a_\mu^{\text{LbyL};\pi^0}$.

With $\Gamma_{\pi^0 \rightarrow \gamma\gamma}^{\text{PDG}}$ [$\Gamma_{\pi^0 \rightarrow \gamma\gamma}^{\text{PrimEx}}$] and current data for $\mathcal{F}_{\pi^0\gamma^*\gamma}(Q^2)$, the error on $a_\mu^{\text{LbyL};\pi^0}$ is $\pm 4 \times 10^{-11}$ [$\pm 2 \times 10^{-11}$], not taking into account the uncertainty related to the off-shellness of the pion. Including the simulated KLOE-2 data reduces the error to $\pm(0.7 - 1.1) \times 10^{-11}$ [2]. The lifetime fixes the normalization of the transition form factor at $Q^2 = 0$, a source of uncertainty in hadronic light-by-light scattering, which has not been considered in most evaluations.

For some models, like vector-meson dominance (VMD), which have only a few parameters that are completely determined by measurements of the transition form factor, this represents the total error in $a_\mu^{\text{LbyL};\pi^0}$. In other models, e.g., those based on large- N_C QCD matched to the OPE, see Ref. [3] and references therein, there are parameters related to the off-shellness of the pion which dominate the total error in $a_{\mu;\text{large-}N_C}^{\text{LbyL};\pi^0} = (72 \pm 12) \times 10^{-11}$. Note that a smaller error does not necessarily imply that a model is better, i.e., closer to reality. Maybe the model is too simplistic. The VMD model is known to have a wrong high-energy behavior with too strong damping, which underestimates the contribution, compared to the large- N_C QCD model, by 15×10^{-11} , i.e., $a_{\mu;\text{VMD}}^{\text{LbyL};\pi^0} \sim 57 \times 10^{-11}$.

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2.11 Charged pion contribution to light-by-light and the muon $g - 2$

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In this talk, I reanalyze the charged pion contribution to the muon anomalous magnetic moment a_μ . Previous estimations [1–3] of this quantity have found a small value ($a_\mu \sim -2 \pm 2 \times 10^{-10}$), but with relatively large model dependence and a correspondingly large uncertainty. Because of the sensitivity of this calculation to higher-order effects, it is important that the models used are as accurate as possible. One check on these models comes from χ PT which governs the behavior of pions at low energies. I present a next-to-leading (NLO) χ PT calculation of the charged pion light-by-light amplitude and compare with a model based prediction [4]. I show that the NLO corrections can indeed be modeled using form factors for the $\gamma\pi\pi$ and $\gamma\gamma\pi\pi$ vertices, but that the existing models are incomplete, missing pion polarizability terms which show up in the $\gamma\gamma\pi\pi$ vertex.

In the language of resonance exchange, the current models include corrections due to ρ exchange, but miss the pion polarizability corrections which are due to exchange of the a_1 axial vector meson. More complete models do exist in the literature [5] which contain both mesons, however, the a_1 exchange in these models suffers from poor UV behavior and cannot be used for the a_μ calculation. Instead, I discuss preliminary work where we model the a_1 exchange using a simple form factor approach. Our model agrees with χ PT at low energies, but has better UV behavior. We have calculated numerically the impact of these a_1 exchanges on the charged pion contribution to a_μ . I present two preliminary results which differ in their treatment of the ρ exchanges: $a_\mu^{\text{VMD}} = -6.7 \times 10^{-10}$ and $a_\mu^{\text{HLS}} = -1.6 \times 10^{-10}$. I conclude that the charged pion contribution appears to be enhanced by the a_1 exchange and may be more significant than previously expected. Consequently, the uncertainty quoted for this quantity should also be increased.

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2.12 Pseudoscalar Transition Form Factors @ KLOE-2 and BGO-OD

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The possibility of new pseudoscalar transition form factor measurements in the KLOE-2 and BGO-OD experiments is presented. Two-photon physics from e^+e^- collisions is explored at DAΦNE [1]; the process $e^+e^- \rightarrow e^+e^-\pi^0$ will be studied at KLOE-2 running the machine at the ϕ peak ($\sqrt{s} = 1.02$ GeV) thanks to new lepton tagger detectors [2]. In particular, the possibility to measure the width $\Gamma_{\gamma\gamma \rightarrow \pi^0}$ with a $\sim 1\%$ level statistical accuracy and the $\pi^0\gamma^*\gamma$ form factor, $F(Q^2)$, at low invariant masses ($0.01 < Q^2 < 0.1$ GeV²) of the virtual photon is considered (see [3] for details). In the BGO-OD experiment [4] pseudoscalar mesons will be photoproduced and the transition form factors will be measured via Dalitz decay processes (see [5]).

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2.13 Meson Decay Program with Crystal Ball at MAMI

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The Institute for Nuclear Physics at the Johannes Gutenberg University in Mainz, Germany, has established a new Collaborative Research Centre (SFB 1044) which has been granted funding by the German Science Foundation (DFG) for up to 12 years. The programme of the SFB 1044 includes studies of electromagnetic as well as neutral η and η' decays. One of the main goals of the SFB 1044 is to significantly improve existing statistics from the Crystal Ball at MAMI experiment on the $\eta \rightarrow e^+e^-\gamma$ decay from roughly 1500 [1] to 30,000 events and to measure the as yet unobserved $\eta' \rightarrow e^+e^-\gamma$ decay. These measurements provide information on meson transition form factors which are also of importance in calculating the hadronic light-by-light contribution to the anomalous magnetic moment of the muon. Furthermore, the neutral decays $\omega \rightarrow \eta\gamma$, $\eta' \rightarrow \omega\gamma$, $\eta/\eta' \rightarrow 3\pi^0$, and $\eta' \rightarrow \eta\pi^0\pi^0$ will be studied to constrain effective field theories of QCD. With the ongoing development of a high-rate Time-Projection-Chamber to be installed at the center of the Crystal Ball the access to all charged meson decay channels will be improved significantly in the near future.

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2.14 Transition Form Factors from CMD-2/CMD-3

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Transition form factors of the π^0 and η mesons have been studied at CMD-2 in a number of various processes described below.

The reactions $e^+e^- \rightarrow \pi^0\gamma$ and $e^+e^- \rightarrow \eta\gamma$ were studied in the broad center-of-mass (c.m.) energy range from 600 to 1400 MeV using the 2γ decay mode of π^0 and η [1]. Earlier ϕ meson decays to $\eta\gamma$ have also been studied using the $\pi^+\pi^-\pi^0$ and $\pi^+\pi^-\gamma$ decay modes [2] and $3\pi^0$ [3].

The $\phi \rightarrow \eta'\gamma$ decay was discovered by CMD-2 in 1997 [4] in the decay chain $\phi \rightarrow \eta'\gamma$, $\eta' \rightarrow \eta\pi^+\pi^-$, $\eta \rightarrow 2\gamma$, the same decay modes with increased statistics were used in [5] and finally with $\eta \rightarrow \pi^+\pi^-\pi^0$ in [6].

Studies of the conversion decays began at the ϕ meson with the first observation of the ηe^+e^- [7] and $\pi^0 e^+e^-$ [8]. Later such decays were studied at the ω meson and searched for at the ρ [9].

The tagged η mesons from the $\phi \rightarrow \eta\gamma$ decays have been also used to study the Dalitz decay $\eta \rightarrow e^+e^-\gamma$, observe for the first time the $\eta \rightarrow e^+e^-\pi^+\pi^-$ decay, and set an upper limit on the decay $\eta \rightarrow e^+e^-e^+e^-$ [7].

Finally, information on transition form factors in a broad mass range was obtained in the processes $e^+e^- \rightarrow \pi^0\pi^0\gamma$ dominated by the $\omega\pi^0$ intermediate mechanism [10] and $e^+e^- \rightarrow \eta\pi^+\pi^-$ dominated by the $\eta\rho$ state [11] (see also Ref. [12] for detailed references.)

In the new experiment with the CMD-3 detector it is planned to study most of these processes with data samples two orders of magnitude higher. A significant background caused by conversion on the detector material will be suppressed using the new drift chamber.

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2.15 Study of the Process $e^+e^- \rightarrow \omega\pi^0 \rightarrow \pi^0\pi^0\gamma$ in c.m. Energy Range 1.05–2.0 GeV at SND

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A preliminary result of the measurement of the cross section for the process $e^+e^- \rightarrow \omega\pi^0 \rightarrow \pi^0\pi^0\gamma$ is presented. The experiment has been performed with the Spherical Neutral Detector (SND) [1–4] at the VEPP-2000 e^+e^- collider [5] in the energy range 1.05–2.00 GeV. The analysis is based on 27 pb⁻¹ collected during 2010 and 2011. The previous measurement [6] used statistics corresponding to 5 pb⁻¹.

Our results are well consistent with the measurements [7, 8] performed by SND and CMD-2 at the VEPP-2M collider at the energies below 1.4 GeV, but significantly (by 20–30%) exceed DM2 [9] data, the only previous measurement at the energy above 1.4 GeV.

We also present comparison of our data on the cross section with the cross section calculated under the CVC hypothesis from the spectral function of $\tau \rightarrow \omega\pi\nu_\tau$ decay measured in the CLEO experiment [10]. A sizable difference is observed between e^+e^- and τ data.

Figure 14 shows the cross section for the process under study according to our data, as well as SND 2000 [7], CMD-2 [8], CLEO [10], and DM2 [9] data. The cross section from [9], measured in the $\pi^+\pi^-\pi^0\pi^0$ channel, was recalculated using the tabulated branching ratios of the ω meson [11]. Under the assumption of vector current conservation, the CLEO cross section was calculated using the spectral function of $\tau \rightarrow \omega\pi\nu_\tau$ decay measured in the CLEO experiment [10].

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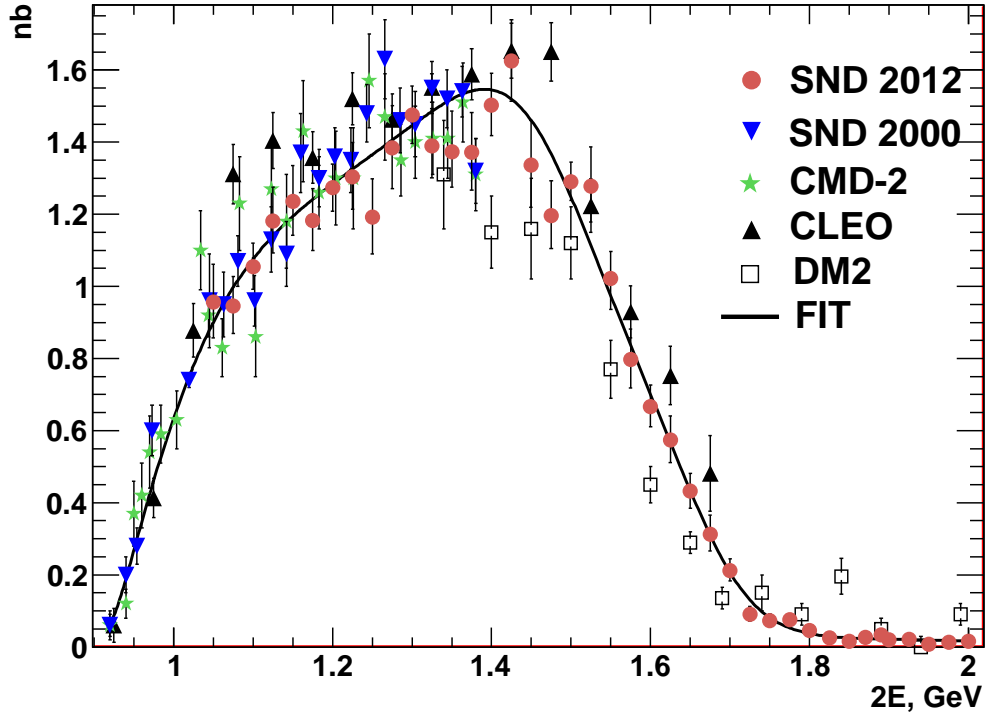


Figure 14: Cross section for the $e^+e^- \rightarrow \omega\pi^0 \rightarrow \pi^0\pi^0\gamma$ process according to the SND 2012 (this work), SND 2000 [7], CMD-2 [8], CLEO [10], and DM2 [9] data. The curve is the result of the joint approximation of the SND 2012 and SND 2000 data.

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2.16 Transition Form Factors with HADES

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Introduction

The High Acceptance Di-Electron Spectrometer (HADES) [1] operates at the GSI Helmholtzzentrum für Schwerionenforschung in Darmstadt, Germany. The scientific program covers a wide range of systematic studies of e^+e^- , pseudoscalar, vector mesons and baryon resonances production in nucleon-nucleon collisions ($p + p$ at 1.25, 2.2, 3.5 GeV and $d + p$ at 1.25 GeV/u), proton-nucleus reactions ($p + \text{Nb}$ at 3.5 GeV) and heavy ion collisions ($\text{C} + \text{C}$ at 1 and 2 GeV/u, $\text{Ar} + \text{KCl}$ at 1.725 GeV/u and $\text{Au} + \text{Au}$ at 1.25 GeV/u). Continuation of this program with pion induced reactions using secondary pion beams at GSI is currently under discussion. One of the important aspects of these studies is the investigation of e^+e^- conversion processes of baryon resonances in elementary and heavy ion collisions.

Results from $p + p$ collisions at 1.25 GeV

The beam energy was selected below η meson production in order to favor $\Delta(1232)$ production and to investigate the Δ Dalitz decay ($\Delta \rightarrow p\gamma^* \rightarrow pe^+e^-$). For this purpose, the ppe^+e^- final state was isolated using the following conditions: $M_{ee} > 0.14 \text{ GeV}/c^2$ and missing mass of the pe^+e^- system equal to the proton mass. This decay probes the structure of the transition $\Delta(J = 3/2) \rightarrow N(J = 1/2)\gamma^*$ in the time-like region ($q^2 > 0$) where the description heavily depends on the model description of the respective electromagnetic form factor [2, 3]. Reconstruction of the complementary channel $pp\pi^0 \rightarrow ppe^+e^-\gamma$ allows for the identification of the Δ^+ resonance as a major intermediate state and further allows to deduce, for the first time, the branching ratio of the Δ Dalitz decay. Furthermore, recently published results on one-pion production in the $np\pi^+$ and $pp\pi^0$ channels [4] and respective comparisons with one-boson-exchange model calculations [5] clearly show dominance of the Δ^{++} and Δ^+ . In parallel, the partial wave analysis (inspired by [6]) has been launched with the aim of a more precise baryon resonance contribution description.

Results from $p + p$ at 2.2 GeV

The higher proton beam energy used in this reaction enabled the investigation of inclusive and exclusive π^0 and η meson production [4, 7] by means of hadron and dilepton decay channels. Dalitz decays of the pion ($\pi^0 \rightarrow \gamma e^+e^-$) and the eta meson ($\eta \rightarrow \gamma e^+e^-$) were compared with the simulation implementing the point-like (QED) and VMD form factor. The results show negligible difference for the π^0 but clearly favors the VMD transition form-factor for the η Dalitz decay.

Results from $p + p$ at 3.5 GeV

At this beam energy higher baryon resonances with isospin $I = 3/2$ and $I = 1/2$ come into play and there is much higher sensitivity to investigate baryon electromagnetic time-like transition form factors (see [3, 8]). HADES results on inclusive e^+e^- production [9] unravel the insufficient contribution to dielectron yields of the known dilepton sources in the $0.4 \text{ GeV}/c^2 < M_{ee} < 0.7 \text{ GeV}/c^2$ range. On the other hand calculations [10] using the two-component quark model (by Wan-Iachello [2]) for the $\Delta(1232)$ transition form factor show better agreement with data. Yet, another possibility for better description of the data is provided by the GiBUU model [10], where the resonance conversion proceeds via intermediate ρN states. The exclusive analysis of $pn\pi^+$, $pp\pi^0$ and pe^+e^- final states [11] brings more constraints to various models. Cross sections of baryon resonances were estimated first in the hadron analysis by simultaneous fitting procedure of invariant masses ($M_{inv}^{p\pi^+}$, $M_{inv}^{n\pi^+}$, $M_{inv}^{p\pi^0}$) and angular distributions ($\cos\theta_{CM}^{p\pi^+}$, $\cos\theta_{CM}^{n\pi^+}$, $\cos\theta_{CM}^{p\pi^0}$) in several bins of the $N\pi$ invariant mass. Then the exclusive ppe^+e^- was reconstructed and compared to the following models:

- Zetenyi-Wolf QED calculations of the resonance conversion rates [12] assuming point-like photon-baryon coupling, which can serve as a lower limit of e^+e^- emission. For the ω/ρ mesons experimentally deduced cross sections are used. The calculation satisfactorily describes the e^+e^- yield at the vector meson pole but cannot fully explain the measured e^+e^- yield for lower e^+e^- invariant mass.
- Krivoruchenko-Martemyanov calculations [13] implement an extended Vector Meson Dominance (eVMD) model for the baryon conversion rates. On the contrary, we observe too large a yield at the vector meson pole and missing yield related to high mass resonances when compared to HADES data.
- Zetenyi-Wolf calculations accomplished with Wan-Iachello form factor (only for $\Delta(1232)$) [2] give a better description, but still a similar treatment of higher resonances is missing. Calculations of the transition form factors for higher Δ and N^* resonances in the time-like region [3] should help to improve the situation.

Yet another important result of the inclusive e^+e^- analysis [9] is the estimation of the upper limit of the branching ratio for the rare electromagnetic decay $\eta \rightarrow e^+e^-$, suppressed by helicity conservation. The value $< 5.6 \times 10^{-6}$ (90% CL) for the η inclusive production in $p + p$ collisions was accepted as a new PDG entry.

Conclusions

The HADES spectrometer provided a wealth of data from $p+p$ collisions at energies 1.25, 2.2 and 3.5 GeV, allowing for systematic studies of meson and baryon resonance production and their decays. In particular, exclusive channels with pion production allow to put constraints on the Δ and N^* cross sections, which are important for a proper description of the resulting dilepton yields. As a consequence, the baryon resonance transition form factors in the time-like region can be investigated, triggering further development in the theoretical description of this interesting process.

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2.17 Some comments on CLEO results and their interpretation

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A personal perspective on the goals of the workshop and on the connections between the experiment and theory in the field of exclusive QCD processes is outlined. A brief review of the current status of hadronic light-by-light (hlbl) scattering contribution to the muon anomalous magnetic moment is presented using selected recent literature [1–3]. It is pointed out that, in spite of impressive experimental and theoretical work over the past decade, the uncertainty in the hlbl contribution has remained the same (approximately 26×10^{-11} (see, *e.g.*, Ref. [3]). It is remarked that, while the new experimental information on exclusive hadronic reactions would be welcome, there is a large theoretical contribution to the uncertainty that could not be trivially reduced using the data. The important role of strong phases in searches for direct CP violation and, generally, Beyond-the-Standard-Model (BSM) physics is emphasized, as also is the need to be able to calculate such phases in hadronic decays of heavy flavors with small theoretical uncertainty. Experimental difficulties of the CLEO analysis [4] of $\gamma^*\gamma \rightarrow \pi^0$ transition form factor are discussed. The trigger algorithms, data-driven measurements and event displays are presented. The interpretation of CLEO measurement in terms of the pion distribution amplitude is discussed and criticized. A discussion of relative merits of various theoretical predictions [5–8] is presented through the eyes of an experimentalist. CLEO results [4] are compared with the BaBar results [9] and the BELLE results [10] (both experiments also reported their results at this workshop). Recent theoretical developments [11] in the framework of the modified perturbative approach are highlighted. The importance of first-principles-based non-perturbative calculations is emphasized. Simple monopole fits to experimental data are criticized and clarified (such interpretations could be used primarily to simplify the comparison among different experiments). The CLEO measurement [12] used to estimate [13] transition form factors of η and η' mesons in the time-like domain is briefly discussed as also is the CLEO measurement [14] of electromagnetic form factors of pion, kaon and proton. To conclude, the importance of future space-like and time-like data for reducing the uncertainty in the hlbl contribution to the muon anomalous magnetic moment is reiterated. It is emphasized that space-like measurements with two highly virtual space-like photons is desirable.

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2.18 A new parameterization for the pion vector form factor

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A new approach to the parameterization of pion form factors is presented and applied to the pion vector form factor for illustration. It has the correct analytic structure, is consistent with recent high accuracy analyses of $\pi\pi$ scattering phase shifts at low energies, and, at high energies, maps smoothly onto the well-known, successful isobar model. With three resonances and three channels ($\pi\pi$, 4π , $\omega\pi$) within the model it is possible to simultaneously describe data on $\pi\pi$ scattering, $e^+e^- \rightarrow \pi^+\pi^-$ as well as $e^+e^- \rightarrow (\text{non-}2\pi)_{\text{isovector}}$. Details of the model can be found in Ref. [1].

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2.19 High accuracy pion phase shifts and light scalar mesons

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We have reviewed our simple and accurate parameterizations of pion-pion scattering up to 1400 MeV, for the three isospin channels with angular momentum up to $\ell = 3$. These parametrizations can be of interest for many hadronic processes, and form factors in particular, as long as they contain two pions in the final state. These fits are first obtained from fits to data but then are also constrained to satisfy three sets of dispersion relations. In particular, we impose three Forward Dispersion Relations up to 1400 MeV, together with three Roy equations and three GKPY Equations up to 1100 GeV. The resulting fits, although still being simple, are nevertheless able to satisfy the analyticity constraints while describing the data. The method is sufficiently powerful to disentangle a longstanding controversy between two sets of data on the inelasticity of the scalar-isoscalar wave around the $f_0(980)$ resonance.

In addition, the use of the partial wave dispersion relations in the form of Roy Equations, and particularly in the form of GKPY equations, also allow us to provide a precise determination of the $f_0(500)$ and $f_0(980)$ poles and residues.

This talk was based on our recent works in [1, 2], to which we refer the reader for further details and references.

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2.20 Roy–Steiner equations for $\gamma\gamma \rightarrow \pi\pi$

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We present a system of Roy–Steiner equations for $\gamma\gamma \rightarrow \pi\pi$ that respects analyticity, unitarity, gauge invariance, and crossing symmetry [1]. In general, the derivation of these equations proceeds similarly to the construction of Roy equations for $\pi\pi$ scattering [2], however, starting from hyperbolic dispersion relations [3] to account for the fact that crossing symmetry intertwines $\gamma\pi \rightarrow \gamma\pi$ and $\gamma\gamma \rightarrow \pi\pi$. Assuming elastic unitarity, the equations for the $\gamma\gamma \rightarrow \pi\pi$ partial waves can be solved by a single-channel Muskhelishvili–Omnès representation with finite matching point [4, 5]. To suppress the dependence of observables on high-energy input, we also consider once- and twice-subtracted versions of the equations, and identify the subtraction constants with dipole and quadrupole pion polarizabilities. We present the results for low-energy cross sections using $\pi\pi$ phase shifts from [6, 7] and pion polarizabilities from [8, 9]. In the same way as $\pi\pi$ Roy equations may be used to determine rigorously the pole parameters of the σ resonance [10], Roy–Steiner equations for $\gamma\gamma \rightarrow \pi\pi$ give access to its coupling to two photons. With input for the polarizabilities from [8], we find a partial width $\Gamma_{\sigma\gamma\gamma} = (1.7 \pm 0.4) \text{ keV}$. Additional information on the pion polarizabilities would further constrain the $\sigma\gamma\gamma$ coupling.

The careful analytic continuation required to obtain the residue at the σ pole shows that calculating a simple “ σ -pole” contribution to hadronic light-by-light scattering amounts to an uncontrolled approximation of the amplitudes relevant for the charged-pion loops. In contrast, the framework presented in this talk, although constructed for on-shell photons in the first place, might be valuable to extend low-energy models for the charged-pion-loop contribution to higher energies [11].

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2.21 A Dispersive Treatment of $K_{\ell 4}$ Decays

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$K_{\ell 4}$ is for several reasons an especially interesting decay channel of K mesons: it allows an accurate measurement of a combination of S -wave $\pi\pi$ scattering lengths, one form factor of the decay is related to the chiral anomaly and the decay is the best source for the determination of various low energy constants of ChPT.

We present a dispersive approach to $K_{\ell 4}$ decays, which fully takes into account final state rescattering effects. Fits to the data of the E865 [1,2] and NA48/2 [3] experiments and results of the matching to ChPT are shown.

Details on the dispersion relation will be available in a forthcoming publication [4].

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2.22 $\eta, \eta' \rightarrow \pi^+\pi^-\gamma$ – A model-independent approach

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We report on a new, model-independent method to analyze radiative decays of mesons to a vector, isovector pair of pions of invariant mass squared below the first significant $\pi\pi$ threshold in the vector channel [1]. It is based on a combination of chiral perturbation theory and dispersion theory. This allows for a controlled inclusion of resonance physics without the necessity to involve vector meson dominance explicitly. In particular, the method is applied to an analysis of the reactions $\eta \rightarrow \pi^+\pi^-\gamma$ and $\eta' \rightarrow \pi^+\pi^-\gamma$. The pertinent decay amplitude factorizes into a universal non-perturbative part, the pion isovector form factor, and a reaction-specific perturbative part, which is governed by a fit to the branching ratio and the spectrum. The method allows experimentalists to parameterize and compare decay data via two parameters only, whereas it allows theorists to relate different radiative decays, *e.g.*, transition form factors, branching ratios, slope parameters etc.

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2.23 The $\omega/\phi \rightarrow \pi^0\gamma^*$ transition form factors in dispersion theory

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We present a study of the $\omega \rightarrow \pi^0\gamma^*$ and $\phi \rightarrow \pi^0\gamma^*$ electromagnetic transition form factors based on dispersion theory, a framework that is derived from fundamental principles like unitarity, analyticity, and crossing symmetry. The analysis relies solely on the input from a previous dispersive calculation of the corresponding three-pion decays [1] and the pion vector form factor. While our calculation of the transition form factor exhibits a clear improvement over naive vector meson dominance, we are—similarly to other theoretical approaches [2]—not able to account for the steep rise towards the end of the physical region found in recent measurements of the $\omega \rightarrow \pi^0\mu^+\mu^-$ decay spectrum by the NA60 collaboration [3, 4]. If such a deviation from the dispersion-theoretical approach has physical significance, it should be found in the related transition form factor of the next-lightest isoscalar vector meson ϕ , where the accessible dilepton invariant mass is somewhat larger and encompasses the region of the ρ resonance. We thus strongly encourage an experimental investigation of the Okubo–Zweig–Iizuka-forbidden $\phi \rightarrow \pi^0\ell^+\ell^-$ decays in order to understand these strong deviations, while additional information on the $\omega \rightarrow \pi^0\gamma^*$ transition form factor to back up the NA60 data would be most welcome. Details of our approach can be found in Ref. [5].

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2.24 A Rational Approach to Meson Transition Form Factors

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The measured $\gamma^*\gamma \rightarrow \pi^0$ transition form factor in the space-like region by the CLEO, CELLO, BABAR, and Belle collaborations are analyzed using the method developed in Ref. [1] which is based on the mathematical theory of Padé Approximants. The method provides a good and systematic description of the low energy region exemplified here with the extraction of the slope a_π and curvature b_π of the form factor in a model-independent way. Their impact on the pion exchange contribution to the hadronic light-by-light scattering part of the anomalous magnetic moment a_μ is also discussed. The main results and the details of the method for the transition form factor can be found in Ref. [2].

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2.25 Radiative transitions of vector mesons

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The conversion decay of a light vector resonance V into a light pseudoscalar meson P and a lepton pair l^+l^- can be used as an electromagnetic probe of the non-perturbative phenomena in the odd-intrinsic-parity sector at low energies. The classic review on the radiative decays of mesons [1] dates back to 1986 and discusses the experimental aspects of $V \rightarrow Pl^+l^-$ measurements. The basic formulae which are typically used in the extraction of the transition form factor from data are also presented therein. The cross-channel processes $l^+l^- \rightarrow PV$ and $P \rightarrow Vl^+l^-$ allow for the extraction of the transition form factor in yet another kinematical regions and are also considered in [1]. Since that time, new measurements of the transition form factors have been performed and new theoretical descriptions of the form factors developed. Also the vector meson radiative transitions have been studied in Lattice QCD [2, 3].

The $VP\gamma^*$ transition amplitude reads

$$\mathcal{M}(V^{(\alpha)} P(k) \gamma^{*(\beta)}(q)) = e g_{VP\gamma} F_{VP\gamma^*}(q^2) \varepsilon^{\mu\nu\alpha\beta} q_\mu k_\nu$$

in terms of the radiative transition form factor $F_{VP\gamma^*}(q^2)$ with $q^2 = M_{l^+l^-}^2$ being the virtuality of the photon coupled to the VP vertex; $\varepsilon^{\mu\nu\alpha\beta}$ is the Levi-Civita symbol, q and k are 4-momenta of the photon and the pseudoscalar meson. The normalization of the form factor is usually chosen such that $F_{VP\gamma^*}(0) \equiv 1$ and the interaction strengths are given by the constants $g_{VP\gamma}$. The radiative decays of vector mesons into a pseudoscalar meson and a real photon provide an access to the values of the $g_{VP\gamma}$ constants via the decay widths:

$$\Gamma(V \rightarrow P\gamma) = |g_{VP\gamma}|^2 \frac{e^2}{96\pi} \left(\frac{M_V^2 - m_P^2}{M_V} \right)^3.$$

The following constants are available from vector meson decays: $g_{\rho\pi\gamma}$, $g_{\omega\pi\gamma}$, $g_{\phi\pi\gamma}$, $g_{\rho\eta\gamma}$, $g_{\omega\eta\gamma}$, $g_{\phi\eta\gamma}$, $g_{\phi\eta'\gamma}$. From the pseudoscalar meson decay widths,

$$\Gamma(P \rightarrow V\gamma) = |g_{VP\gamma}|^2 \frac{e^2}{32\pi} \left(\frac{M_V^2 - m_P^2}{M_V} \right)^3,$$

one can access the following constants: $g_{\rho\eta'\gamma}$, $g_{\omega\eta'\gamma}$. Up to date, all the above mentioned decays have been studied experimentally [4]. The pattern of $g_{VP\gamma}$ values gives us the primary information on the flavor $SU(3)$ symmetry realization in the light meson sector and, in particular, on the meson mixing. Hence a big attention from the theory side to the radiative decays [5–9].

Among the existing theoretical descriptions of the $VP\gamma$ transitions there are the “traditional” vector meson dominance (VMD) ansatz [10]; the effective Lagrangian approaches to a (modified) VMD [11–13]; the extended Nambu-Jona-Lasinio (eNJL) model [14]; the hidden local symmetry Lagrangian approach (HLS) [15–18]; the linear sigma model with

constituent quarks [19]; quark models [20, 21] and others. The state of the art in the field of $VP\gamma$ transitions with the real photon is that in many theoretical approaches one can have a simultaneous fit of the widths $\Gamma(V \rightarrow P\gamma)$ with a reasonable quality.

There were also numerous theoretical studies of the $VP\gamma^*$ transitions with the virtual photon, e.g., the HLS calculations [16], the eNJL model approach [14], an extended VMD approach [22], the Dyson-Schwinger equation studies [23], the light-cone quark model prediction [24]. The most recent theoretical advances in the modeling of the $VP\gamma^*$ transition form factors [25–28] were partly motivated by a drastic discrepancy between a novel CERN SPS NA60 experiment data [29, 30] and a naive VMD ansatz prediction for the $\omega \rightarrow \pi\gamma^*$ transition form factor. The published experimental information on the $V \rightarrow P\gamma^*$ is the following: Lepton-G (Serpukhov): $\omega \rightarrow \pi\mu^+\mu^-$ [31]; CMD-2 (Novosibirsk): $\omega \rightarrow \pi e^+e^-$ [32]; SND (Novosibirsk): $\phi \rightarrow \eta e^+e^-$ [33], $\omega \rightarrow \pi e^+e^-$ [34]; NA60 (CERN): $\omega \rightarrow \pi\mu^+\mu^-$ [29, 30]. The form factors are extracted from the decay line shape using the formula [1]

$$\begin{aligned} \frac{d\Gamma(V \rightarrow P\mu^+\mu^-)}{dQ^2} &= \frac{\alpha}{3\pi} \frac{\Gamma(V \rightarrow P\mu^+\mu^-)}{Q^2} \left(1 + \frac{2m_\mu^2}{Q^2}\right) \sqrt{1 - \frac{4m_\mu^2}{Q^2}} \\ &\times \left(\left(1 + \frac{Q^2}{M_V^2 - m_P^2}\right)^2 - \frac{4M_V^2 Q^2}{(M_V^2 - m_P^2)^2} \right)^{3/2} |F(Q^2)|^2. \end{aligned}$$

A promising complementary process is $e^+e^- \rightarrow PV$ which allows to study the $VP\gamma^*$ form factors in the region of time-like photon virtuality above the PV threshold. For example, the modeling of the process $e^+e^- \rightarrow \omega\pi^0$ has been considered in the NJL model [35], non-relativistic quark model [36], an effective Lagrangian approach [37], etc. The main experimental information on $e^+e^- \rightarrow \omega\pi^0$ is the following: SND data near the phi meson [38], from the $\omega\pi^0$ threshold up to 1.4 GeV [39] and in the energy range 1.1 – 1.9 GeV [40]; there is also CMD-2 data in the energy range 0.92 – 1.38 GeV [41]. The form factors can be extracted from the cross section using the formula [1]

$$\sigma_{e^+e^- \rightarrow VP}(s) = |g_{VP\gamma} F_{VP\gamma^*}(s)|^2 \frac{e^4}{12\pi s^2} 4\sqrt{s} \left(\frac{(s - (M_V + m_P)^2)(s - (M_V - m_P)^2)}{4s} \right)^{3/2}.$$

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2.26 Decays with Vector Mesons

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While the vector-meson dominance (VMD) model describes some reactions as, e.g., the pion and eta form factors (pion and eta, respectively, coupled to two real or virtual photons), it fails to describe others as, e.g., the omega-pion form factor (omega coupled to pion and virtual photon) [1]. For calculating decays including vector mesons, we use a new counting scheme treating both the light pseudoscalar and the light vector-meson nonet on the same footing [2, 3]. Using this counting scheme, one can describe the omega-pion form factor very well [3, 4]. Additionally, the decay width for the decay of omega into three pions agrees very well with the experimental data [5]. If one in addition includes the Wess–Zumino–Witten action as the leading-order contribution from chiral perturbation theory, the scattering e^+e^- into three pions is well described [6]. Furthermore, the results for the pion- and eta-transition form factors are in numerical agreement with VMD [7, 8] for one real and one virtual photon. If both photons are virtual, we find significant deviations from VMD.

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2.27 Meson form factors in amplitudes for three-body B decays

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A summary of two phenomenological analyses of the rare three-body B decays is given. We study CP violation and the contributions of the strong interactions between the pion and kaon pairs in the $B^\pm \rightarrow \pi^+\pi^-\pi^\pm$ and $B^\pm \rightarrow K^+K^-K^\pm$ decays [1, 2]. The B -decay amplitudes are derived in the QCD factorization approach supplemented with the inclusion of the long distance $\pi^+\pi^-$ and K^+K^- interactions. The form factors, corresponding to the transitions from B to light mesons or resonances and to transitions between light mesons, are important components of the decay amplitudes. A unitary model is constructed for the scalar non-strange and strange form factors in which three scalar resonances $f_0(500)$, $f_0(980)$ and $f_0(1400)$ are naturally incorporated. These form factors satisfy the constraints coming from the chiral perturbation theory.

Using our model the Dalitz plot analyses of the $B^\pm \rightarrow \pi^+\pi^-\pi^\pm$ and $B^\pm \rightarrow K^+K^-K^\pm$ decays can be improved by reducing a number of fitted free parameters. The model can be extended to study CP violation in other charmless decays and to analyze new high-statistics data from Belle, BaBar, LHCb and from future super-B factories. Application of a similar approach to the charged and neutral B decays into $K\pi^+\pi^-$ is described in [3].

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2.28 ChPT calculations of form factors

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An overview on Chiral perturbation theory calculations of form factors was presented [1]. The main focus was given on the form factors related to the lightest meson, pion, namely: pion decay constant [2], pion vector and scalar form factor, radiative pion decay and transition form factor. Finally, due to its importance for the basis of Chiral perturbation theory, also an overview of the kaon decay form factors, namely those related to K_{l4} decay, was given. A pure calculation within the effective theory can be extended using further methods: resonance chiral theory [3], leading logarithm calculations [4], resummed chiral perturbation theory, etc.

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2.29 Pion-photon transition form factor at the crossroads

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Using light-cone sum rules, we retrofit the CELLO, CLEO, BaBar, and the brand-new Belle data for the processes $\gamma^*\gamma \rightarrow \pi^0$ and $\gamma^*\gamma \rightarrow \eta$, and $\gamma^*\gamma \rightarrow \eta'$ beyond the level of the first two Gegenbauer coefficients in the pion distribution amplitude $\varphi_\pi(x, Q^2)$ [1]. The next-to-leading order QCD perturbative contribution and the twist-four term are taken into account explicitly, while the next-to-next-to-leading order radiative correction [2] and the twist-six term are included by means of theoretical uncertainties. Evolution of the pion distribution amplitude is also taken into account at the next-to-leading-order level. We claim that the observed bifurcation of the Belle and the BaBar data above 10 GeV^2 is artificial, arguing that the BaBar data which show an auxetic behavior with Q^2 are incompatible with the standard framework of QCD, while the Belle data saturate and scale with Q^2 as predicted by QCD. We also examine the predictions for $(3/5)Q^2 F^{\gamma^*\gamma n}(Q^2)$ for the state $|n\rangle = (1/\sqrt{2})(|u\bar{u}\rangle + |d\bar{d}\rangle)$, extracted from the CLEO and the BaBar data on the η and η' using the quark-flavor mixing scheme. We find very good agreement between our predictions and both data sets which implies that the shapes of the π^0 and the non-strange component $|n\rangle$ of the η and η' mesons are quite similar to each other with little room for a significant flavor-symmetry violation in the pseudoscalar meson sector of QCD [3, 4]. These distribution amplitudes are best described by the two-parameter model of [5], which was extracted from QCD sum rules with nonlocal condensates, and is double-humped but endpoint suppressed. The Chernyak-Zhitnitsky and the asymptotic distribution amplitudes were found before [6–8] to be incompatible with the CLEO data at the level of 4σ and 3σ , respectively. Because the theoretical approaches to describe the antithetic behavior of the Belle and the BaBar data above 10 GeV^2 are hardly comparable to each other, we consider an interpretation of these data against some common standard rather questionable [9].

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2.30 Light pseudoscalar meson decays into lepton pair

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A recent publication by the KTeV Collaboration of the branching ratio for the $\pi^0 \rightarrow e^+e^-$ decay [1] renews the interest to the old problem of the light pseudoscalar meson decays into a lepton pair. From theoretical point of view the real part of the decay amplitude consists of the structure-independent (dominant) and the structure-dependent (small) parts. The first part contains the large logarithms of the ratio m_e/m_π . The second one starts from the unknown Low Energy Constant χ_P . This constant, besides the above process, enters amplitudes of another observed process: the decay $\eta \rightarrow \mu^+\mu^-$ [2], the hadronic part of the light-by-light scattering to muon $g - 2$ [3]. In [4] it was shown that the constant χ_P can be defined as the inverse moment of the pion transition form factor and rather precisely extracted by using CLEO data [5]. Then, the branching for the $\pi^0 \rightarrow e^+e^-$ decay can be predicted in a model-independent way. It turns out that the theoretical prediction deviates from the experimental number by 3.3σ .

At present, the principal point is to perform new measurements of the light pseudoscalar meson decays into a lepton pair as a test of the Standard Model. Besides the pion decay, the most interesting modes are the muon modes of the η and η' meson decays, where theoretically not only lower, but also upper bounds are predicted [4, 6]. Recently, new experimental upper bounds on the decay $\eta \rightarrow e^+e^-$ were obtained [7, 8]. Present and future measurements [8–11] of the pseudoscalar meson transition form factors at low momenta (WASA-at-COSY, KLOE-2, BESIII, CMD, HADES) will help to define the constant χ_P more precisely.

The confirmation of the deviation between experiment and theory will indicate existence of hypothetical Dark Matter particles with low mass (of order 10–100 MeV) (see [12]).

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2.31 The hadronic light-by-light contribution to the muon anomalous magnetic moment

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The hadronic light-by-light contribution to the muon anomalous magnetic moment will become a limiting factor in the accuracy of the theory prediction in the Standard Model in the near future. A fairly recent update of the situation can be found in the presentations at the INT workshop in February-March 2011 [1].

There are at present three main calculations of this quantity, BPP [2], HKS [3] and MV [4], all following the separation scheme of [5]. We have recently studied the contributions of the different momentum regions in more detail. This work was started in [6] and for the pion-loop we now understand [7] the large difference in the results in the full VMD model [2] and the hidden local symmetry model [3]. We have also studied the influence of L_9 and $L_9 + L_{10}$ which was recently suggested to be important [8]. This method also allows to clearly see where the quark-loop contributes [7].

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